AN INVESTIGATION OF WAVE-TYPE DISTURBANCES OVER THE TROPICAL SOUTH-ATLANTIC

Eugenio Jose Ferreira Neiva

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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OVER THE TROPICAL SOUTH-ATLANTIC

by

Eugenio Jose Ferreira Neiva

March 1975

Thesis Advisor: C. P. Chang

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Investigation of Wave-type Disturbances over the Tropical South Atlantic Ocean		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; March 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Eugenio Jose Ferreira Neiva		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE March 1975
		13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

** Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(Page 1) S/N 0102-014-6601 |

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Cross-spectral analysis results indicate that the disturbance has a wavelength of about 6000 km, propagates westward at a rate of about 11° longitude per day, has a slight NW-SE tilt and tilts backward in the vertical.

The energetics of the disturbance could not be determined. Examination of the shear of the wind field and the tilt of the disturbance indicates that barotropic instability is unlikely to be an energy source.

An Investigation of Wave-Type Disturbances
over the
Tropical South-Atlantic Ocean

by

Eugenio Jose Ferreira Neiva
Lieutenant, Brazilian Navy
B. S., Escola Naval do Brasil, 1963

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
March 1975

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ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. Chih-Pei Chang, under whose advice this investigation was performed.

This research was accomplished while the author was pursuing graduate studies in meteorology at the Naval Postgraduate School under sponsorship of the Brazilian Navy.

The author is grateful to Mr. Roy Jenne, who provided the NMC Tropical Analysis data, from the NCAR Tape Library; to the Commander, Naval Weather Service Command, who provided the radiosonde data for Ascension Island; and to the Instituto de Pesquisas Espaciais and the Diretoria de Hidrografia e Navegacao, who provided the data of the Brazilian station.

I. INTRODUCTION

Wave-type disturbances of synoptic scale in the tropical regions have been extensively studied in recent years. Among others, the works of Yanai et al. (1968), Wallace and Chang (1969), Chang (1970a), Chang et al. (1970b), Nitta (1970), Reed and Recker (1971) and Wallace (1971) for the Central and Western Pacific and Burpee (1972, 1974) for North Africa have documented the existence of such disturbances with periods ranging from four to six days and wavelengths from 2000 to 8000 km. These studies used either the spectral analysis, composite techniques or a combination of both techniques.

Due to the absence of an adequate observational network, the weather over the equatorial South Atlantic Ocean is generally represented by its mean, undisturbed state. There are few references in the literature about the perturbations caused by organized synoptic systems. Yet, there is evidence of disturbances crossing the west coast of Africa into the ocean between the equator and 5° S (Mbele Mbong 1974) and the east coast of South America into the continent at approximately 10° S (Ramos 1974).

The availability of wind data for five levels of the troposphere from analysis produced by the Tropical Analysis Group at the National Meteorological Center suggested an investigation about the presence of wave-like disturbances in

the equatorial South Atlantic area. This tropical analysis is performed at 12 hour intervals based on all available conventional radiosonde observations, satellite derived winds and aircraft reports. Due to the scarcity of reporting stations, the data in the equatorial South Atlantic are fairly limited. However, the NMC analysis may still contain some information of the synoptic-scale disturbances passing through this area. Since the amplitude of the disturbances that can be picked up by the objective analysis scheme are expected to be small and easily obscured by the persistence which forms a substantial portion of the total variance of the wind field, these disturbances may be very difficult to discern by analysis of individual weather maps on a routine basis. On the other hand, the chance of detecting them should be considerably improved when long-period time series are analyzed.

The purpose of this study is to perform such an analysis of the NMC data using spectral and cross-spectral techniques in the hope that some information on wave-type disturbances in the equatorial South Atlantic contained in the data can be obtained.

II. DATA

A. BASIC DATA SET

In addition to the NMC analysis mentioned earlier, two other sets of data were made available during the course of the work. A description of each set follows.

The NMC analysis contains the zonal (u) and meridional (v) wind components for five levels of the troposphere, namely, 700, 500, 300, 250 and 200 mb. These winds are available at rectangular grid points evenly spaced by five degrees of longitude on a Mercator projection. The grid distance is approximately 556 km at the equator (Bedient and Irwin 1970). The area selected for this study is bounded by 45^{o}W, 15^{o}E, 10^{o}S and the equator, including 39 grid points with 13 at each latitude (Figure 1). In total, 390 time series were generated, each series containing twice-daily data for a period of 441 days (882 data points) from 1200 GMT, 23 January 1971 to 0000 GMT, 8 April 1972.

The second set of data, provided by the National Climatic Center, consisted of surface and radiosonde observations for a few stations in the African Coast and Ascension Island (8^{o}S, 14^{o}W). However, only data at Ascension Island were analyzed because the excessive amount of missing data at the other stations rendered their time series unsuitable for spectral analysis. For Ascension Island, 28 time series of daily

observations of horizontal wind components, temperature and mixing-ratio at eight pressure levels (1000, 850, 700, 500, 400, 300, 250 and 200 mb) were generated, spanning a period of 361 days from 4 January 1971 to 31 December 1971 (no mixing ratio for the four upper levels). Since on the average about 40% of the data are missing in each time series, even these data were considered marginally usable for a spectral analysis.

The third set came from the Brazilian space research institute (Instituto de Pesquisas Espaciais) through the hydrographic agency of the Brazilian Navy (Diretoria de Hidrografia e Navegacao). It consists of daily pilot-balloon observations at height levels 180 m apart at several stations and radiosonde observations of temperature and relative humidity at several others, all in the Brazilian coast. However, only the lower levels at the station Parnaiba Airport (3°S, 42°W) were considered to have sufficient data in the time domain to make spectral analysis worthwhile. Time series of u and v components were thus generated at this station for each of the 12 lowest height levels, resulting in a total of 24 series encompassing the period from 18 June 1971 to 31 December 1971. These series represent approximately the lowest 2 km of the atmosphere.

B. PREPARATION OF THE DATA

After the time series were generated, all missing data were linearly interpolated. The fraction of the interpolation

for the NMC data series is always less than 8.0%. For Ascension Island this amount is increased to about 40% of the series, with missing data more or less evenly scattered in the entire period. The amount of interpolation at Parnaiba Airport is close to 24% with no large gaps. These percentages suggest that the spectral results obtained from the station data, especially those of Ascension Island, are less reliable than the grid-point results.

Each time series was then subjected to a high-pass filter, with the primary purpose of avoiding leakage of variance from the very low frequencies, which is quite predominant due to the persistence in the data, especially the zonal wind component. The weights of the filter were obtained from a normal curve with standard deviation 50/3 half-days for the twice-daily series and 25/3 days for the daily series (Holloway 1958). The Nyquist frequency is 1 cycle per day (cpd) for the twice-daily series and 2 cpd for the others. No measure was taken to avoid "aliasing" from frequencies higher than the Nyquist frequency since not much variance is thought to exist in them.

The theoretical response function of the filter is greater than 95% for frequencies higher than 0.05 cpd (period of 20 days), and, for all practical purposes, 100% for frequencies higher than 0.08 cpd (period of 12.5 days). An estimate of the actual response function was obtained by determining the

variance spectrum of the series before filtering ($G_x(f)$) and after filtering ($G_y(f)$) and taking the positive square root of their ratio ($H^2(f)=G_y/G_x$). This estimate is displayed in Figure 2.

After filtering, the time series at the grid points were reduced from 882 to 784 points. The Ascension Island series were reduced to 313 points and the Parnaiba Airport series to 149 points.

The variance spectrum for each series was then computed with a maximum lag of 25 days, which implies 50 lags of one-half day for the grid-point series and 25 lags for the station series. The cross-spectra were computed whenever possible, between series at different levels (inter-z), different longitudes (inter-x), different latitudes (inter-y) and between the two wind components.

All the spectral computations were performed at the W. R. Church Computer Center of the Naval Postgraduate School using the program BMDO2T of the UCLA Biomedical Statistical Program Package.

III. TEST OF SPECTRAL SIGNIFICANCE

The significance of the spectral results was tested using a procedure recommended by Mitchell, et al. (1966). This procedure is briefly described below along with pertinent considerations.

The BMD02T program used to calculate the variance spectrum begins by computing the mean of the data and subtracting it from each value of the series. The serial autocorrelation coefficients (R_n) for lags from zero to M are then calculated, where M (maximum number of lags chosen) $<$ N (number of points in the series). The cosine transforms of these M+1 lag autocorrelation values are then computed, yielding M+1 "raw" estimates of the variance spectrum, each value being a rough measure of the total variance in the original series that is contributed by wavelengths near each harmonic of the fundamental wavelength of the analysis (2M). The raw estimates are then smoothed by a "hamming" window function (a 3 term weighted moving average with weights equal to 0.23, 0.54 and o.23, respectively), with the purpose of deriving a consistent estimate of the final spectrum in terms of M+1 discrete estimates.

To evaluate the cross-spectrum, the program first calculates the serial cross-correlation coefficients in the same form as for the autocorrelation coefficients. After that, the cospectrum is obtained by determining the cosine transforms of

these cross-correlation coefficients and the quadrature spectrum is obtained from the sine transforms of the cross-correlation coefficients. Both the co-spectrum and the quadrature spectrum are smoothed by the "hamming" method. From the co-spectrum and the quadrature spectrum, the amplitude and phase of the cross-spectrum are computed and the coherence square between the two series is determined.

In this study, each computed variance spectrum was tested by fitting a "null" hypothesis continuum spectrum. The choice of a "null" continuum was based on the observed fact that the lag-one serial autocorrelation coefficient R_1 of the series analyzed differs markedly from zero, being typically of order of 0.70 for the u series and 0.55 for the v series. This indicates the possible large influence of simple persistence to the series. If a series is made up entirely of random variations and persistence, it may be written as

$$X_{i+1} = R_1 X_i + \varepsilon_{i+1} \quad ,$$

where ε_{i+1} is the random part of X_{i+1} independent of any of the preceding terms of the series and $R_1 X_i$ is the part of X_{i+1} "explained" by X_i. Applying the same reasoning for X_{i+2}, etc, and combining the equations thus obtained, it can be seen that the sample serial autocorrelation coefficients must approximately bear an exponential relationship, $R_n = R_1{}^n$. It follows that the autocorrelation function must decrease exponentially and approach zero asimptotically (see, for example, Brooks and

Carruthers 1953, or Mitchell 1963). In such case, the appropriate "null" continuum should also be a decreasing function whose shape depends on the value of the lag-one autocorrelation coefficient. Assuming that R_1 is an unbiased estimate of the unknown lag-one autocorrelation coefficient for the population, this "null" continuum may be described by

$$S_K = \overline{S}\ (\ (1-R_1{}^2)/(1+R_1{}^2 - 2R_1\ \mathrm{COS}\ (K/M)\ )\ )\quad ,$$

where $\overline{S}$ is the average of all M+1 "raw" spectral estimates in the computed spectrum, K is the harmonic number and S_K is the variance per unit frequency interval.

The first step of the testing procedure is to verify whether the autocorrelation coefficients for the various lags of a given time series drop exponentially or not. Only in the affirmative case, the chosen model is considered appropriate and the variance spectrum may be compared to the "null" continuum in order to determine if the series contain some other form of non-randomness in addition to persistence. The value of the spectral estimate for each frequency interval is compared with the local value of the "null" continuum. If it differs from the continuum by a statistically significant amount, the hypothesis of non-randomness other than persistence in the frequency band examined is accepted.

The statistic associated with each spectral estimate (i.e., with the variance per interval of frequency) is the ratio of the magnitude of each spectral estimate to the local magnitude of the continuum. This statistic has been shown

to be distributed according to a chi-square (χ^2) divided by the degrees of freedom (DOF). The degrees of freedom are given by

$$DOF = (2N-M/2)/M \quad ,$$

where N is the sample size and M is the maximum lag. It follows that, for a chosen level of significance (0.05 in the present study), confidence limits can be established by multiplying the "null" continuum by the proper value of χ^2/DOF. The "null" hypothesis may be then phrased as follows: The only form of non-randomness in the series is persistence. If the estimates of variance per interval of frequency exceed the confidence limits, the hypothesis is rejected and it is concluded that there exists periodicity in the frequency band under consideration. Figures 3(a) and (b) illustrate the analysis procedure. They were generated from the 1000 mb v-series at Ascension Island. Figure 3(a) shows the autocorrelation function R_n (full line). The dashed line represents the exponentially decreasing function $R_1{}^n$. As $R_1{}^n \geq R_n$ for the first few lags, the series is considered to fit the first-order autoregressive model, i.e., to be affected only by simple persistence. R_1 is then used to generate the "null" spectrum, which, multiplied by the 95th percentage point of the χ^2/DOF, gives the confidence limit represented by the dashed line in Figure 3(b). Since the estimate of the variance at the frequency 0.20 cpd exceeds the confidence limit, it is concluded that there is activity in the series at this frequency, with 95% confidence.

It should also be noticed that the described procedure applies to an a priori chosen frequency interval, which is based on considerations independently derived. In the present study, the frequency band from 0.16 to 0.24 was selected based on the results from previous studies in several other areas that used not only spectral analysis but also composite techniques (as mentioned in the Introduction). The need for an a priori selection of a frequency band for investigation is due to the fact that for a sample variance spectrum with, say, 100 spectral estimates, on the average 5 of these values are expected to lie beyond the 95% confidence limit. So, if a particular spectral estimate is chosen for study merely because it is the largest in the spectrum, the usual test of significance is not applicable, and a different principle of decision theory has to be applied (Brooks and Carruthers 1953, Mitchell 1963).

The grid-point series have 784 data points after filtering; the number of lags chosen was 50 (25 days). These values led to spectral estimates with approximately 31 degrees of freedom and χ^2/DOF = 1.46. The latter value becomes 1.52 for the Ascension series (25 lags used) and 1.77 for the Parnaiba series.

Out of approximately 400 series analyzed, only less than 1.0% do not fit the linear autoregressive "null" continuum. Thus, more than 99% of the series were tested according to this procedure.

Confidence limits for the coherence square estimates were also established using the probability points of the distribution of squared coherence compiled by Amos and Koopmans (1963). The degrees of freedom of these estimates are given by 1.25 N/M which is appropriate for the hamming smoothing function.

It should be noticed that this test for significance of the coherence square implies a "null" hypothesis of zero population coherence. Such a model is thought to be a fairly good assumption in the case of the 700- and 500- mb series of the grid-point data and the series for the station data, as they generally show very low values of background coherence. For the upper levels, a background of high values of coherence were found. The appropriate confidence limits for the coherence square should be raised to take into account the already high level of background coherence. This was not done in the present study because the variance spectra for those levels generally do not show significant peaks in the frequency interval studied.

IV. RESULTS

A. VARIANCE SPECTRA

1. 700 mb and 500 mb Grid-Point Series

The variance spectra of u and v at the 700 mb level for all grid-points are shown in Figure 4. At this level, 45 of the 78 series show significant spectral peaks in the frequency band of 0.16-0.24 cpd, with 24 peaks in the v component and 21 in the u component. In general, they are more pronounced away from the equator. At the 500 mb level (Figure 5), 50 series show significant peaks in this frequency band and 34 of them are in the v component. Generally, the spectral peaks seem to be somewhat more prominent as compared to those at 700 mb. In addition, no strong latitudinal preference is detected at this level.

In order to better establish the significance of the spectral peaks for the 0.16-0.24 cpd frequency band, a composite spectrum was constructed for each wind component and level by averaging the spectra at the 13 grid-points of each latitude. The composite spectrum was then compared to an "average" "null" continuum calculated from the average of the lag-one correlation coefficient of the 13 series. The resultant curves are shown in Figure 7. It can be readily seen that the v component has a well defined, significant spectral peak in the frequency band being considered at 500 mb at all three latitudes.

At 700 mb the spectral peaks are less pronounced but significant variance in the v component still shows up at $5^{o}S$ and $10^{o}S$ for the 0.20-0.24 cpd frequency band. Thus these results clearly indicate the significance of oscillations of the v component in the frequency range of 0.16-0.24 cpd, which corresponds to a quasi-periodicity of approximately 4-6 days. On the other hand, no corresponding peaks in the composite u-spectra can be found, except for a slight indication of variance at 500 mb level at the equator. Therefore a major portion of the variance of the 4-6 days oscillations, at least as reflected in the NMC analysis, seems to be confined to the v component.

The frequency band 0.16-0.24 cpd is the a priori chosen band of interest for this study. In the subsequent sections all the cross-spectral results discussed are the average values for this frequency band.

2. Upper-Level Grid-Point Series

The number of significant spectral peaks at the three upper levels (200, 250 and 300 mb) of the NMC analysis is greatly reduced. Furthermore, the spectra for both wind components at these levels resemble each other, having the characteristics of a red-noise spectrum because most of their variance is in the very low frequencies. The lag-one autocorrelation coefficients for these series range between 0.65 and 0.75, somewhat higher than those for the series at 500 and 700 mb. Thus persistence seems to dominate the total variance at the upper levels. Since inter-level cross-spectra

results (to be discussed later) also indicate a very high coherence between these levels at all frequencies, it is felt that they are mainly constructed from extrapolations of a single data level. For this reason, only the results of the 200 mb level are shown to represent the upper troposphere.

The variance spectra at 200 mb for each grid-point are depicted in Figure 6. It is clear that, except for a few isolated grid-points, mainly at 10°S, no significant spectral peak can be found. The composite spectra at this level, which is also included in Figure 7, show no significant activity at all. It is therefore concluded that the 4-6 day oscillations are mainly confined to the middle and lower levels of the NMC data.

3. Station Series

At Parnaiba Airport, spectra of u and v series for the 12 height levels from surface to 2070 m were computed from the available pilot-balloon data (not shown). The v series have significant spectral peaks in the 0.16-0.24 frequency band in 10 of the 12 levels, while the u series exhibit peaks only at the 4 lowest levels (surface to 612 m). Because of the strong similarity of the spectra at the various levels, a composite spectrum for v series was generated by averaging the 12 v spectra in the vertical and compared to a "null" continuum, in the same manner earlier described for the composite grid-point spectra (Figure 8). A distinct spectral peak centered at the 0.20 cpd frequency, or the 5 day period, is clearly visible.

For Ascension Island, spectra of the u and v components, temperature and mixing-ratio at the eight previously mentioned pressure levels were computed. The spectra of the u series do not show any significant peak and only the 1000-mb v spectrum has a significant peak around the 0.20 cpd frequency band (Figure 3). The temperature and mixing-ratio series exhibit very small fluctuations and their spectra (not shown) resemble that of a random series, with no feature being distinguishable above the background noise.

The variance spectra for Ascension Island are expected to resemble those for the neighbouring grid points. Since this is not quite the case, a careful comparison between the data at Ascension Island and those at the two grid points just north and south of the island ($5^{o}S$, $15^{o}W$ and $10^{o}S$, $15^{o}W$) was performed. A visual inspection of the unfiltered 700 mb u and v series at the grid points for both 0000 and 1200 GMT show them to be in fairly good agreement with the once-daily series at Ascension Island, except that the latter series are much smoother due to the excessive interpolation of missing data. The higher frequencies at Ascension Island are therefore strongly damped. Cross-spectra between the Ascension Island and grid point series were also computed. The coherence-square values are generally large for the lower frequencies and decrease towards higher frequencies but remain above the 95% confidence limit for frequencies around 0.20 cpd. These facts support the hypothesized cause for the apparent disagreement between the grid points and the station

results, namely, the excessive amount of missing data at Ascension Island (approximately 40%).

B. CROSS-SPECTRA

1. Inter-Level Cross-Spectra

The inter-level (inter-z) cross-spectra for the grid-point wind components were determined using the 500 and 250 mb levels as the base series. The cross-spectra with 250 mb as the base series reveal very high values of coherence square at all frequencies between this level and the two other upper levels (200 and 300 mb). The phase differences are also very small across the spectrum at all grid points. This result, plus the previously mentioned resemblance of the variance spectra for these levels, are attributed to the special procedure used by the NMC analysis. In this region, the data are usually available at only one upper level at each location, which may be from either aircraft reports or satellite-derived winds. These data are then extrapolated to the other levels, resulting in the strong similarity between the time-series at the three upper levels at most grid points.

The cross-spectra between the 200, 500 and 700 mb series for both wind components are shown in Figure 9. At each grid point a line is used to indicate the vertical tilt of the disturbance axis between the 700, 500 and 200 mb levels. This line was drawn according to the phase differences between the 500 mb level and the other levels. Only phase values

associated with a coherence-square value that meets or exceeds the 95% confidence limit are plotted. It is seen that only about 1/3 of the grid points show significant inter-level cross-spectral values. Surprisingly, the relation between the 500 mb and 200 mb is somewhat better than that between 500 mb and 700 mb. For those phase values associated with significant coherence squares, the lower level usually leads the upper level, suggesting an upward propagation direction. This is generally true for both components, except for the southeastern corner of the region where the v component shows a downward propagation direction between 500 and 700 mb. In almost all cases the phase differences between two "adjacent" levels are less than 0.20 cycle.

The inter-z cross-spectra for Parnaiba Airport between the 12 levels from surface to 2070 m (800 mb) were computed with the 801-m level series as the base series. The resultant coherence squares for u are generally below the 95% confidence limit. The coherence squares for v, on the other hand, all exceed this limit and the phase differences are plotted in Figure 10. It can be seen that the waves propagate upward above the 1170 m level (880 mb), consistent with the results obtained for the grid-point series. Below this level, the waves show a downward propagation direction with some variations between 801 and 414 m. In general the phase differences are quite small being less than 0.20 cycle between all levels except the surface.

2. Inter-Longitude Cross-Spectra

At each level the time-series of each component at 15°W were used as the base series to cross with the other grid-points at the same latitude. The resultant inter-x cross-spectra are plotted in Figure 11. In each panel the phase difference with coherence value satisfying the criterion of 95% confidence are plotted as a function of longitudinal distance between the base series and the other series. With only a few exceptions, usually occuring at the easternmost grid-points, the coherence-square values between longitudes are generally quite high. At all latitudes and levels the v component shows a quite consistent east-west phase relationship. The eastern series always lead the western ones, indicating a westward propagation direction. The slope of the plotted curves are also very similar and show a longitudinal difference of about 55° or approximately 6000 km for a complete cycle. This value thus represents the east-west wavelength of the waves. The u component generally indicates a smaller phase difference between longitudes and not so consistent from level to level as it is for the v-series, although the lower levels still indicate a westward propagation direction. Since the v component has most of the variance in this frequency band, the result of 6000 km is taken as the estimate for the horizontal wavelength.

3. Inter-Latitude Cross-Spectra

The inter-latitude (inter-y) cross-spectra for both components are presented graphically in Figure 12. Here each line connecting three grid points at the same longitude and level indicates the phase differences between $5^{\circ}S$ (the base series), the equator and $10^{\circ}S$. Most u series and all v series have significant inter-y coherence squares that meet the 95% confidence limit. With the exception of a few cases, the u series tilt NW-SE, the average phase difference between the equator and $10^{\circ}S$ being close to 0.18 cycle. The v series generally have very small phase differences between latitudes with the average phase difference indicating a very slight NW-SE tilt for the waves. Since most of the variance is in the v component, these phase relationships indicate a slight NW-SE tilt of the axis of the waves.

4. Inter-Parameter Cross-Spectra

The cross-spectra between the u and v series at each grid point and level (not shown) have only about 15% of the pairs with significant coherence. For these pairs, a 1/2 cycle out-of-phase relationship between the two components is generally indicated. For non-divergent motion such phase implies a NW-SE tilt of the wave axis (Gruber 1974).

V. SUMMARY AND CONCLUSION

ı investigation about the existence of synoptic-scale ;ype disturbances over the tropical South Atlantic Ocean, ;he equator to $10^{o}S$ was carried out using the spectral ;is technique.

ıe main data base came from the NMC tropical analysis is available at $5^{o} \times 5^{o}$ longitude grid points and con- of winds at five levels in the troposphere, spanning a l of approximately 14 months. In addition, one year's from Ascension Island and a Brazilian coast station, iba Airport, were examined. The data were first organized time series, with missing data being linearly interpolated. h-pass filter was then applied to the series to avoid ge of the variance through the lobes of the spectral w in the computation of the spectra.

statistical test of the variance spectra was performed suming a "null" continuum with simple persistence as the form of non-randomness. The a priori selected frequency under scrutiny is from 0.16 to 0.24 cpd (4 to 6 day periods). found, with 95% confidence that oscillations are indeed nt in the frequency band in the meridional component of 00 and 500 mb levels of the NMC grid point data and in the evel station data.

of homogeneity. As a consequence, the degree of freedom for the composite spectrum is greatly increased, which implies a confidence higher than 95%. It is still possible that this periodicity may be due to some procedure inherent to the NMC objective analysis, such as the use of the 12 hour forecast as the first guess or the scheme of adjusting anomalous reports to climatology. Due to the lack of an adequate number of conventional stations in the equatorial South Atlantic region, the possibility that this 4 to 6 day quasi-periodicity is largely a result of the NMC analysis cannot be completely ruled out. However, in view of the facts that perturbations with the same periodicity have been established beyond doubt in the Pacific, Caribbean and North-African regions and that the same periodicity is found at the lower levels of the two stations used in this study, it is felt that there is a reasonable degree of certainty about their existence in the equatorial South Atlantic. In any case, further study would be worthwhile especially if better data can become available.

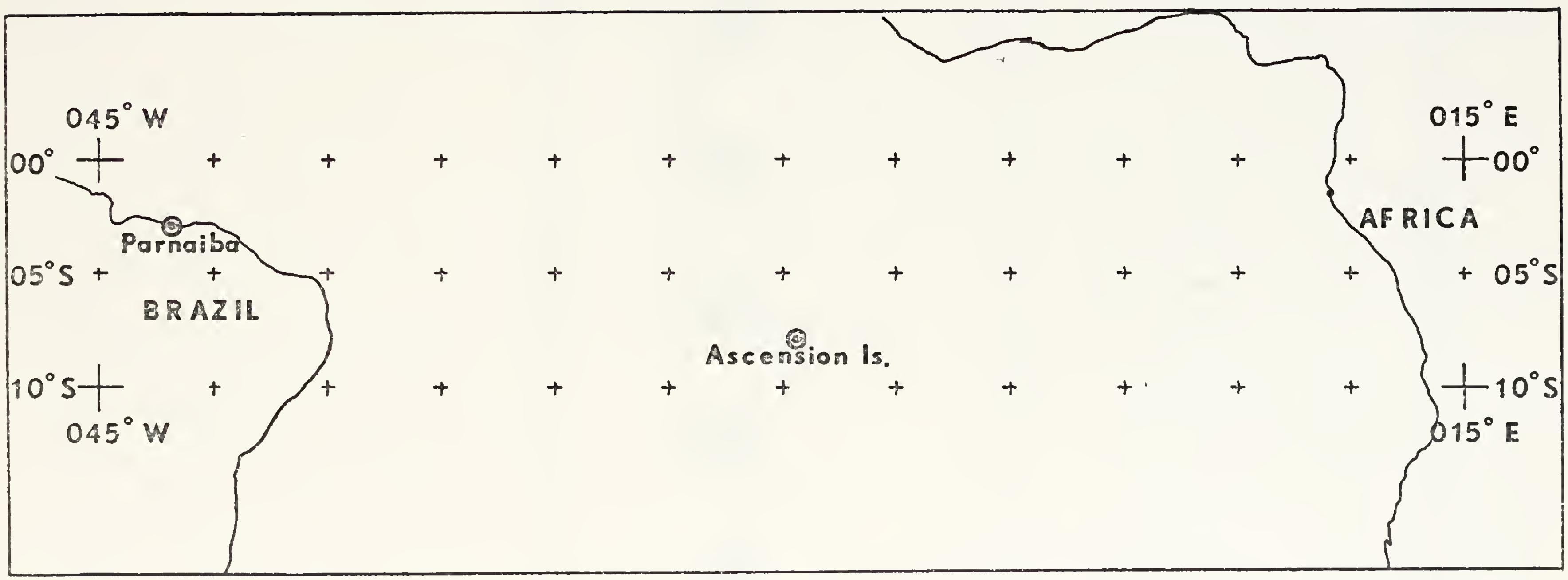

FIGURE 1 - Area of study. Points of the NMC's Tropical Grid are denoted by crosses. Ascension Island and Parnaiba Airport are the two land stations used.

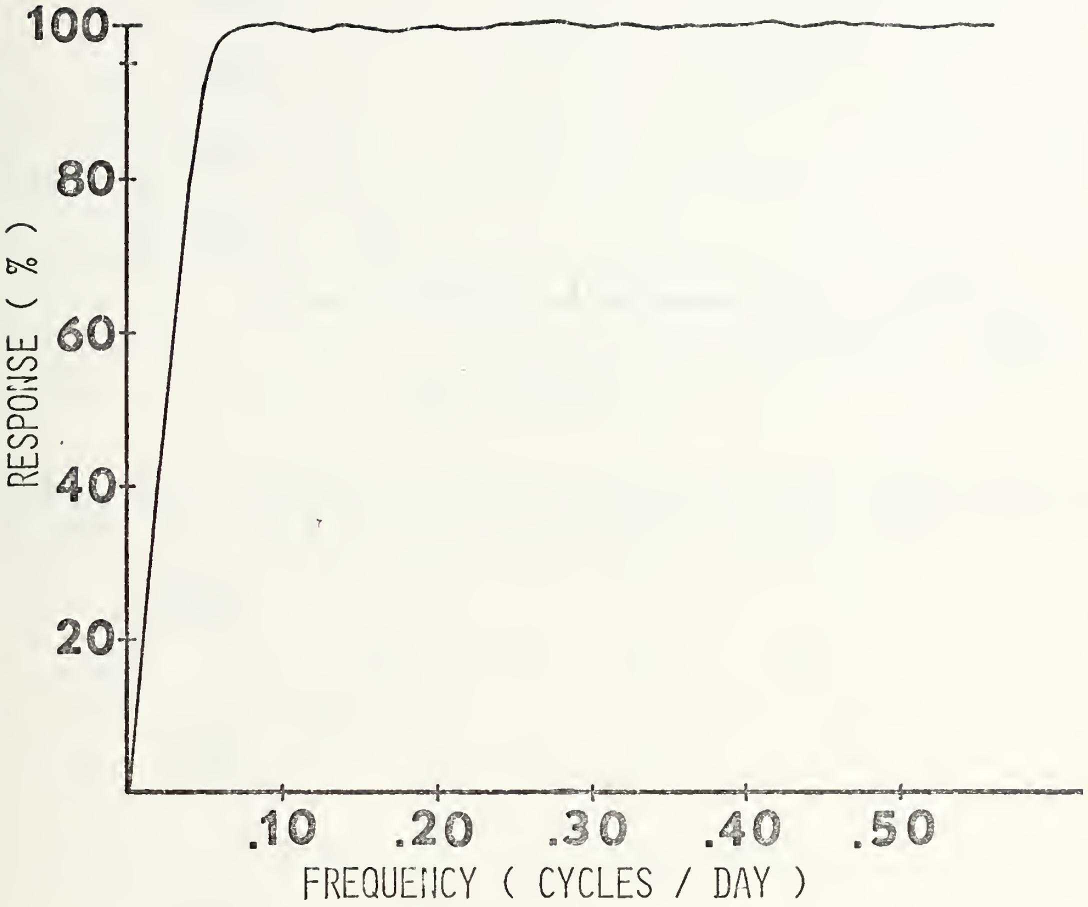

FIGURE 2 - Estimate of the response function of the high-pass filter.

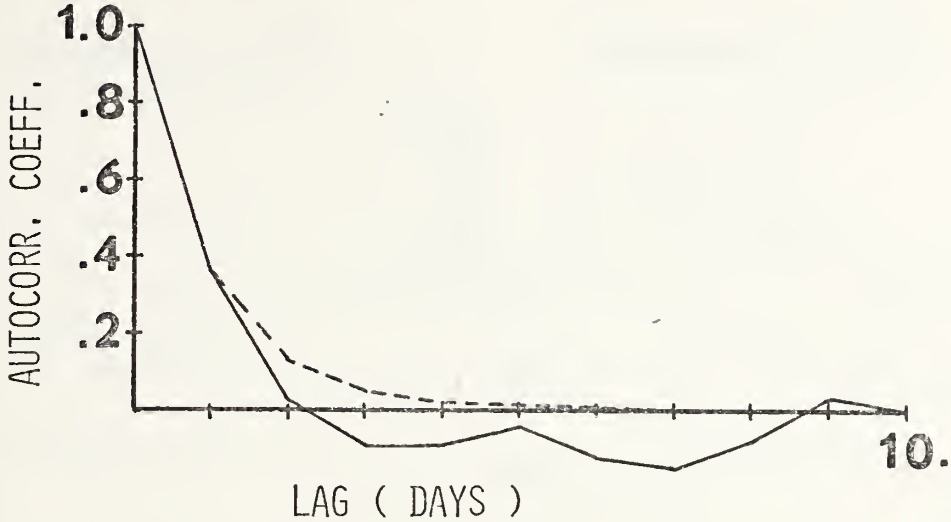

FIGURE 3(a) - Autocorrelation function (full line) and the function R_1^n (dashed line). See text for details.

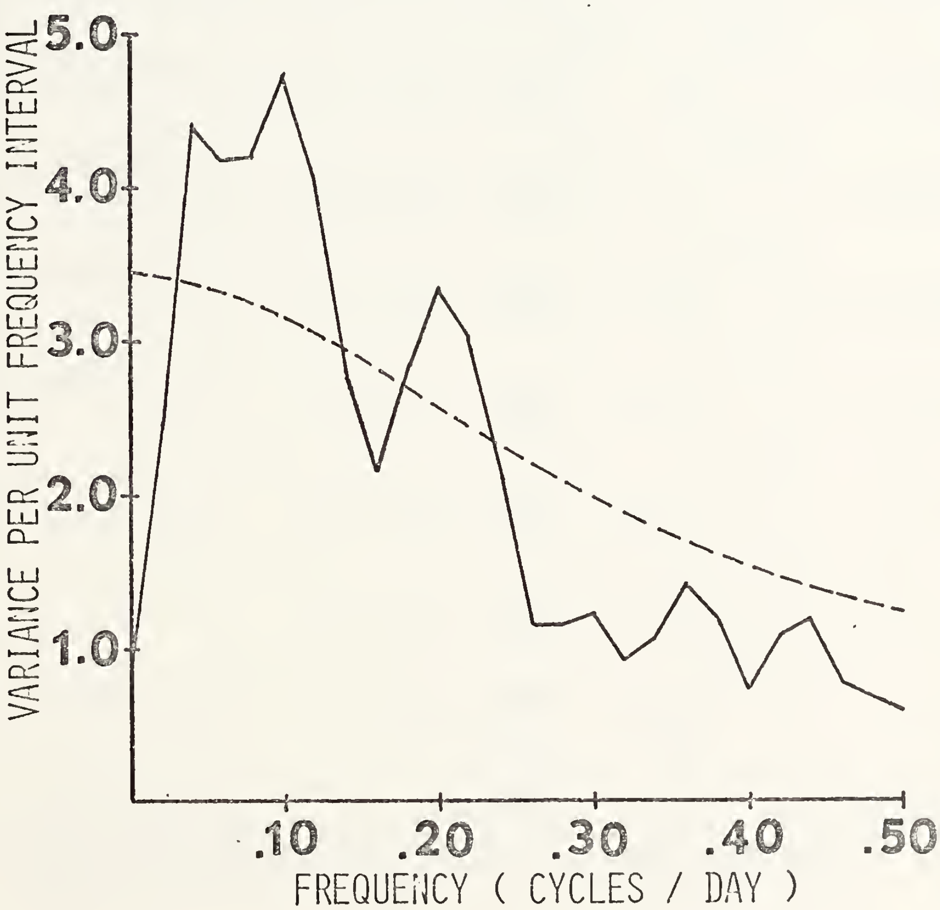

FIGURE 3(b) - Variance spectrum (knot^2 per 2 π /50 day^{-1}) of the 1000 mb v series at Ascension Island. Dashed line is the 95% confidence limit.

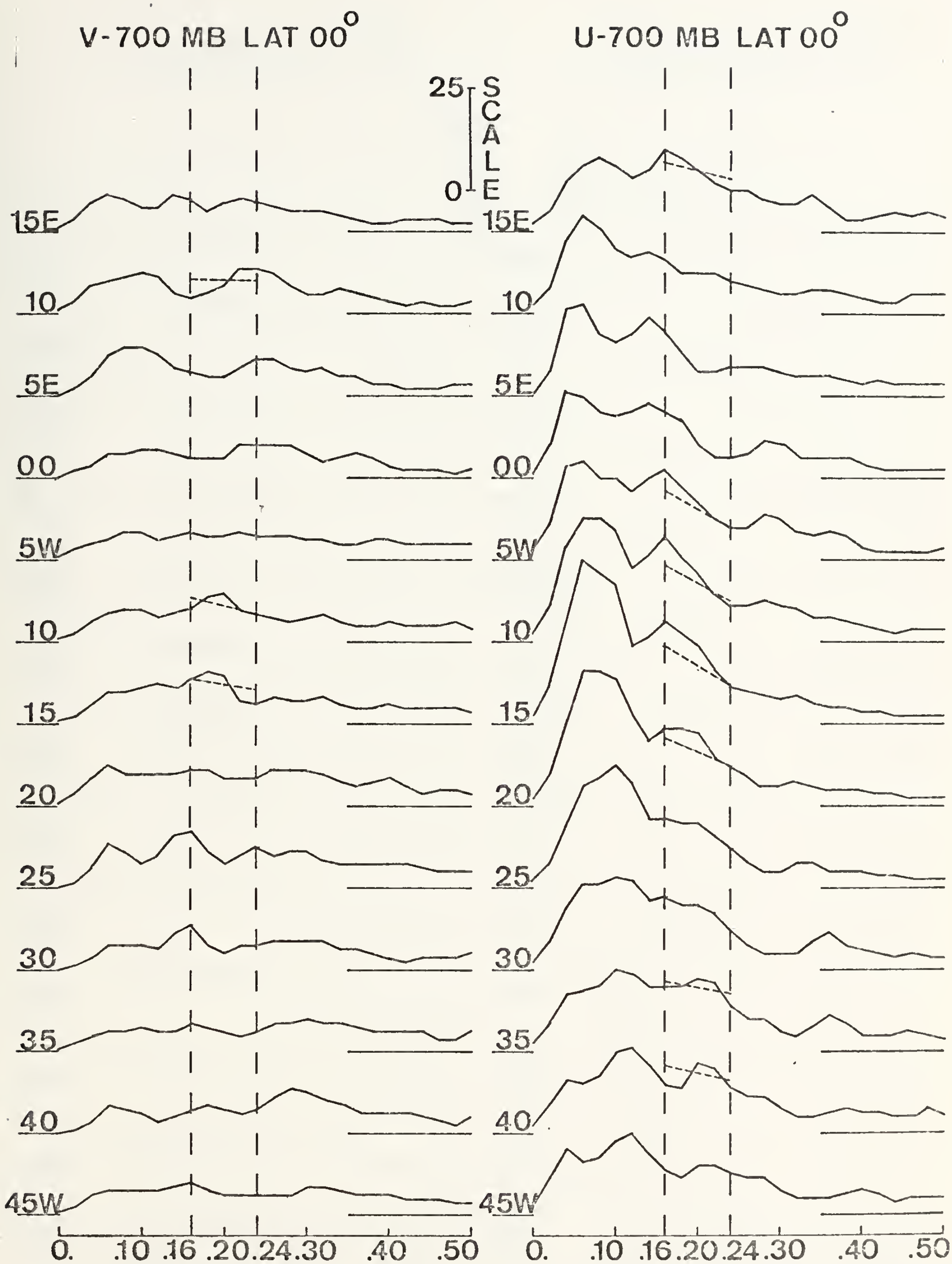

FIGURE 4(a) - Variance spectra (knot^2 per 2 π /50 day^{-1}) of 700 mb grid point winds at the equator. The 95% confidence limit (dashed line) is plotted in the 0.16-0.24 cpd band whenever the variance exceeds the limit.

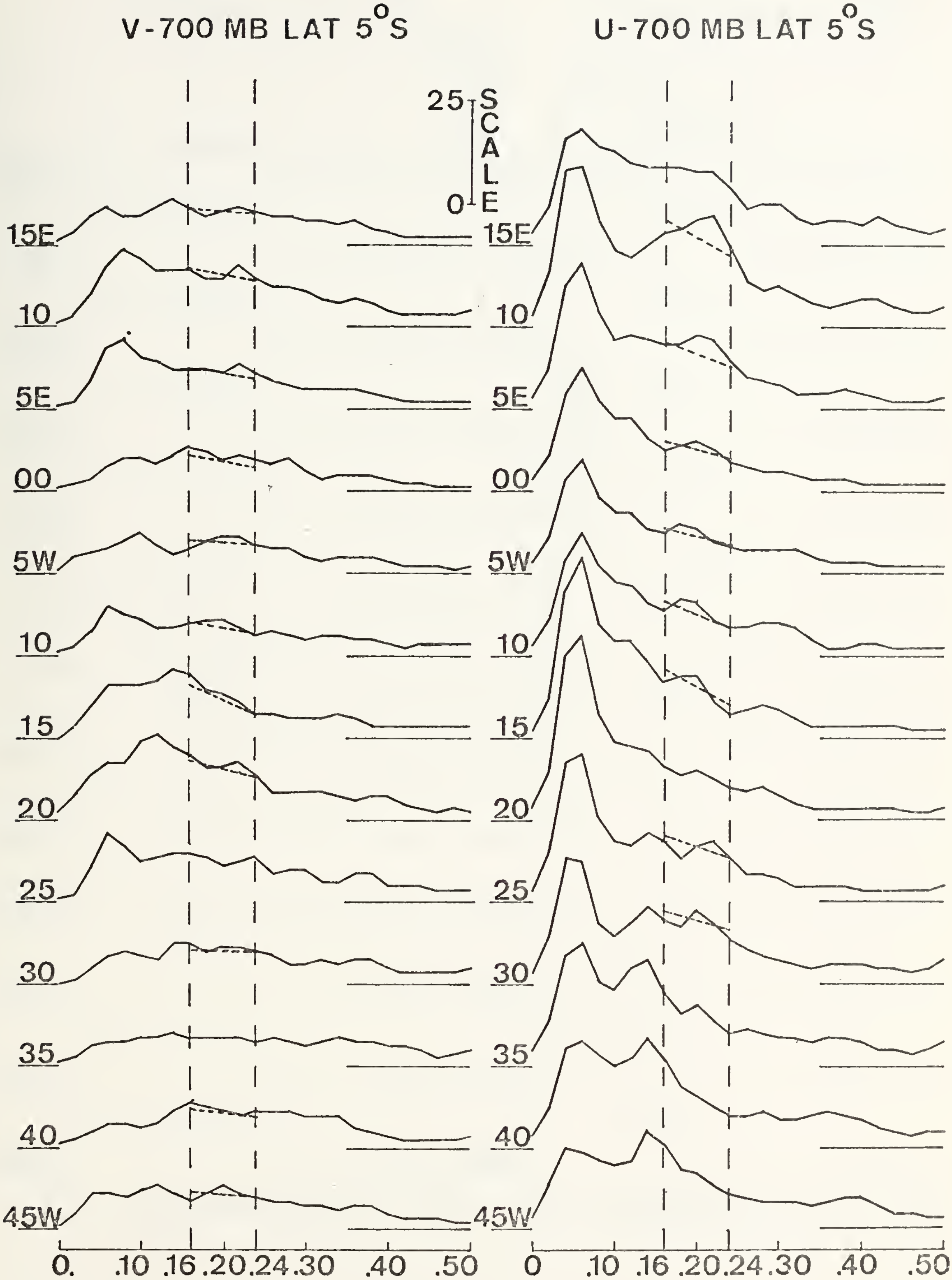

FIGURE 4(b) - Same as FIGURE 4(a), except for 700 mb and 5^oS.

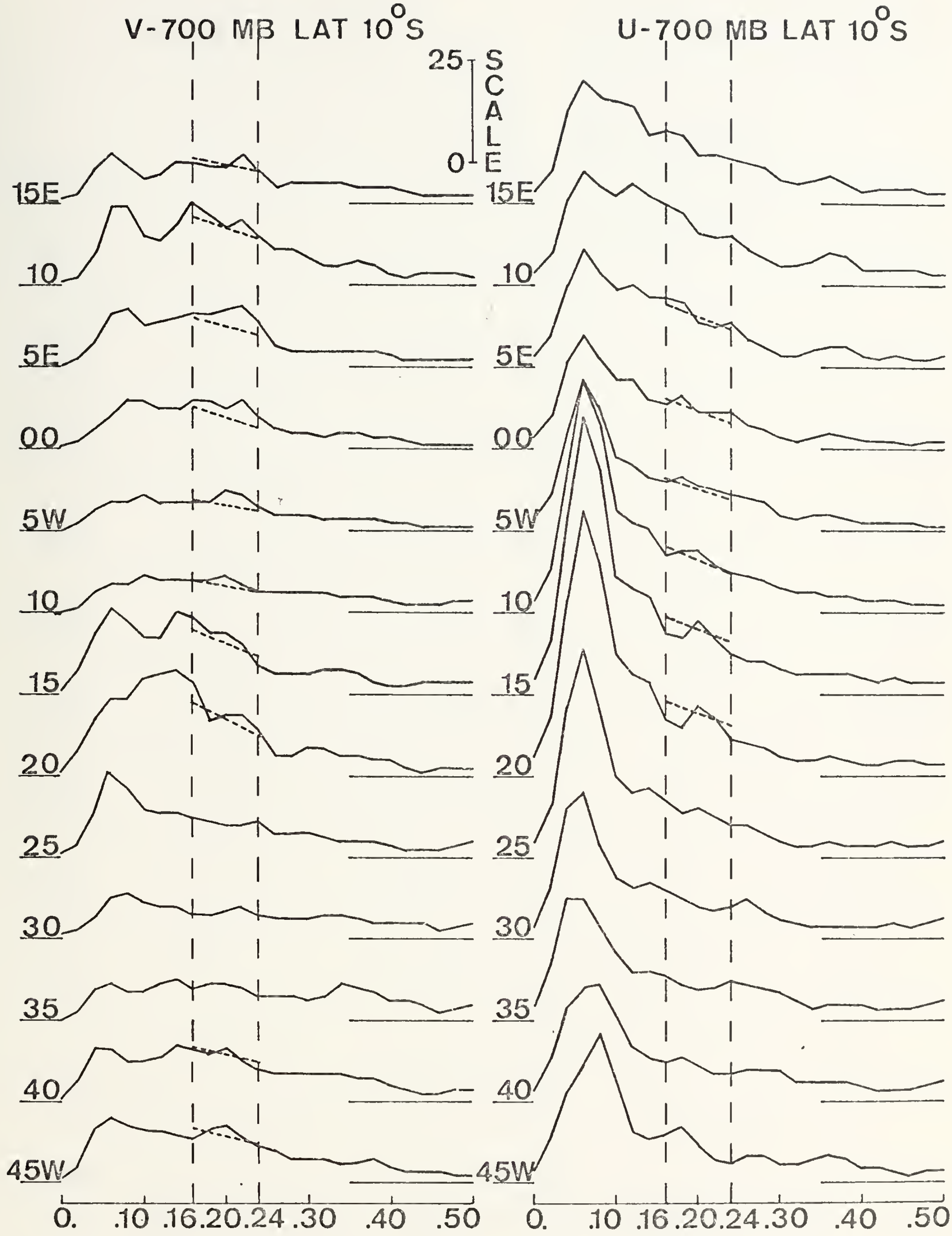

FIGURE 4(c) - Same as FIGURE 4(a), except for 700 mb and 10°S.

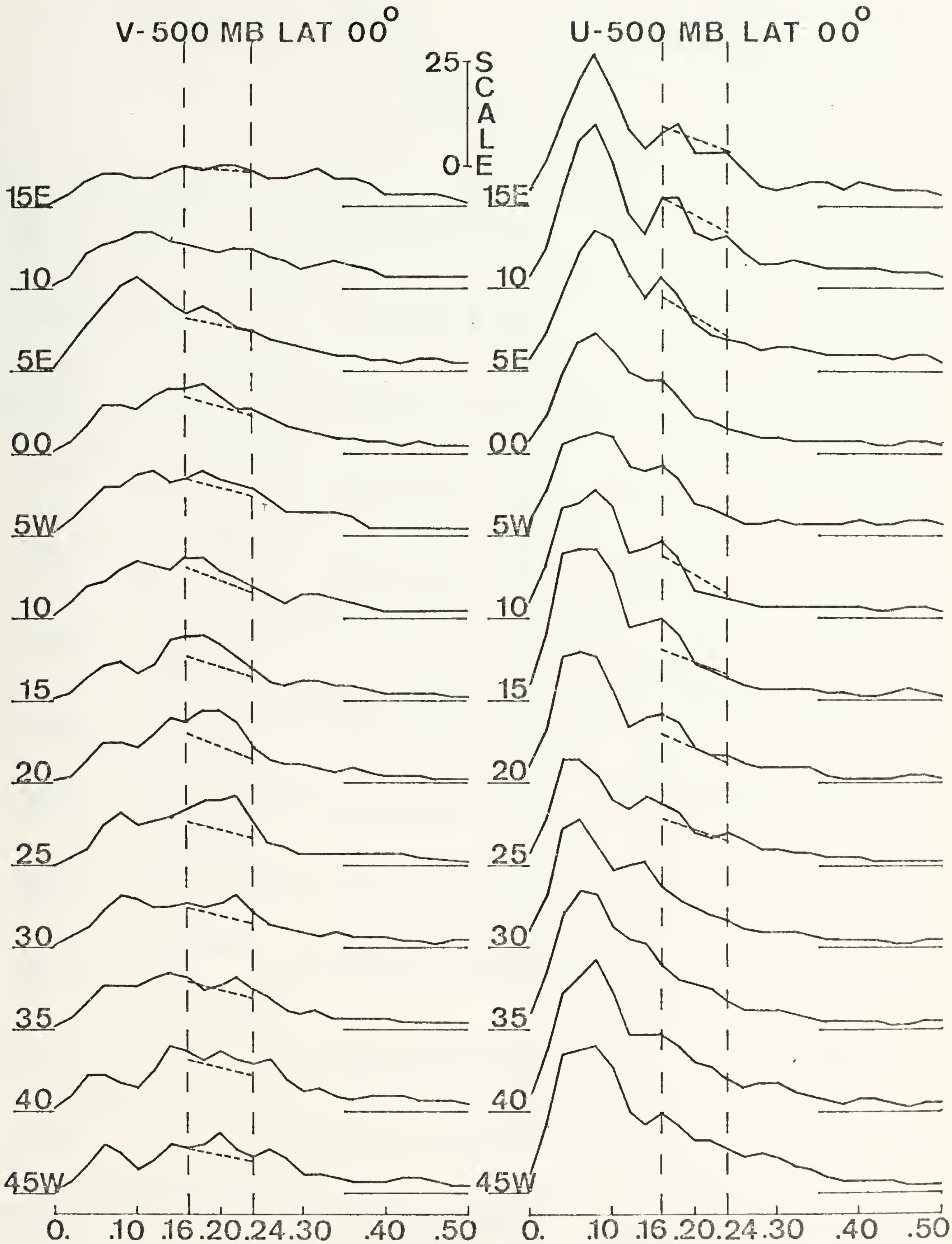

FIGURE 5(a) - Same as FIGURE 4(a), except for 500 mb and the equator.

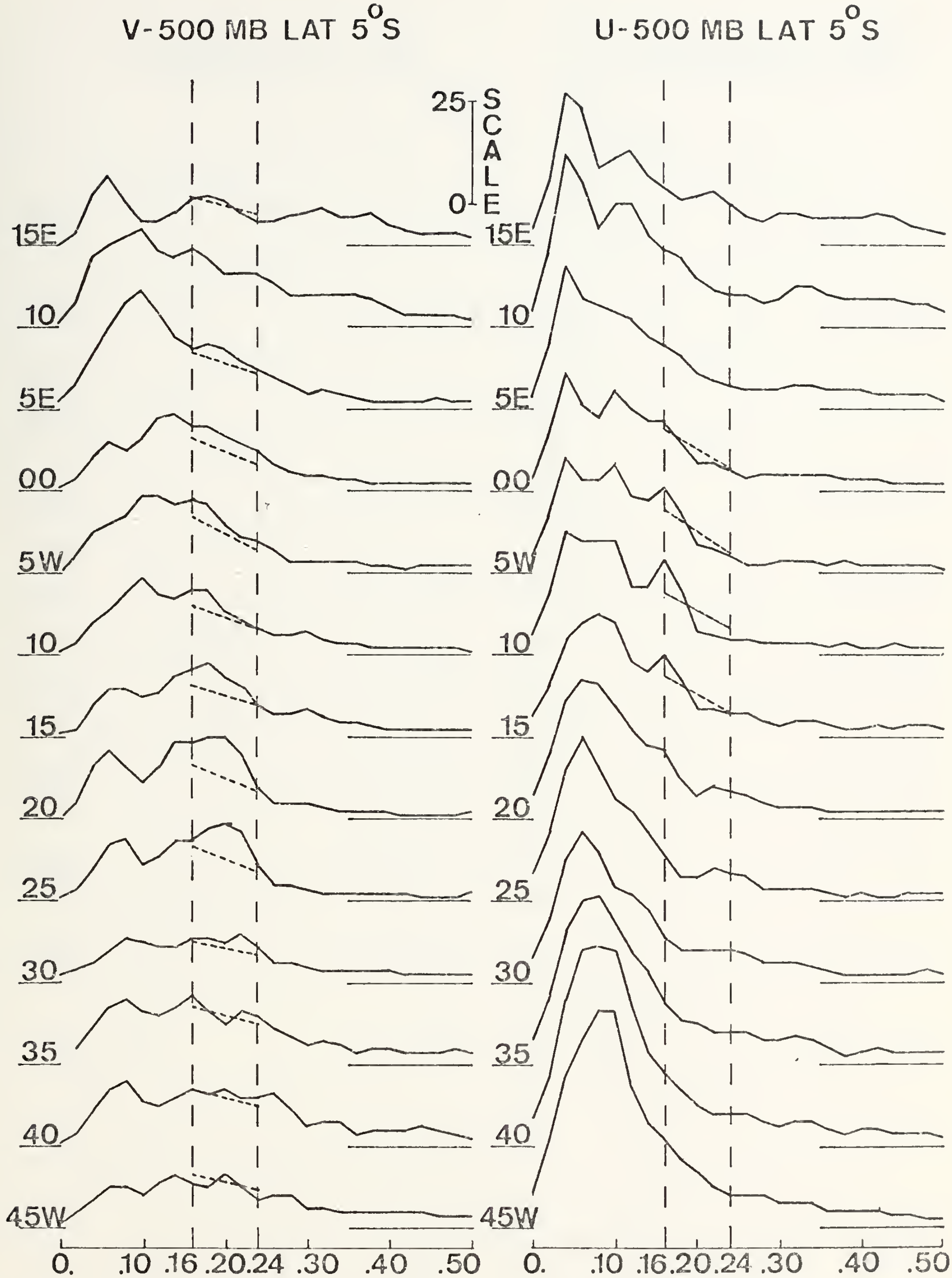

FIGURE 5(b) - Same as FIGURE 4(a), except for 500 mb and 5^{o}S.

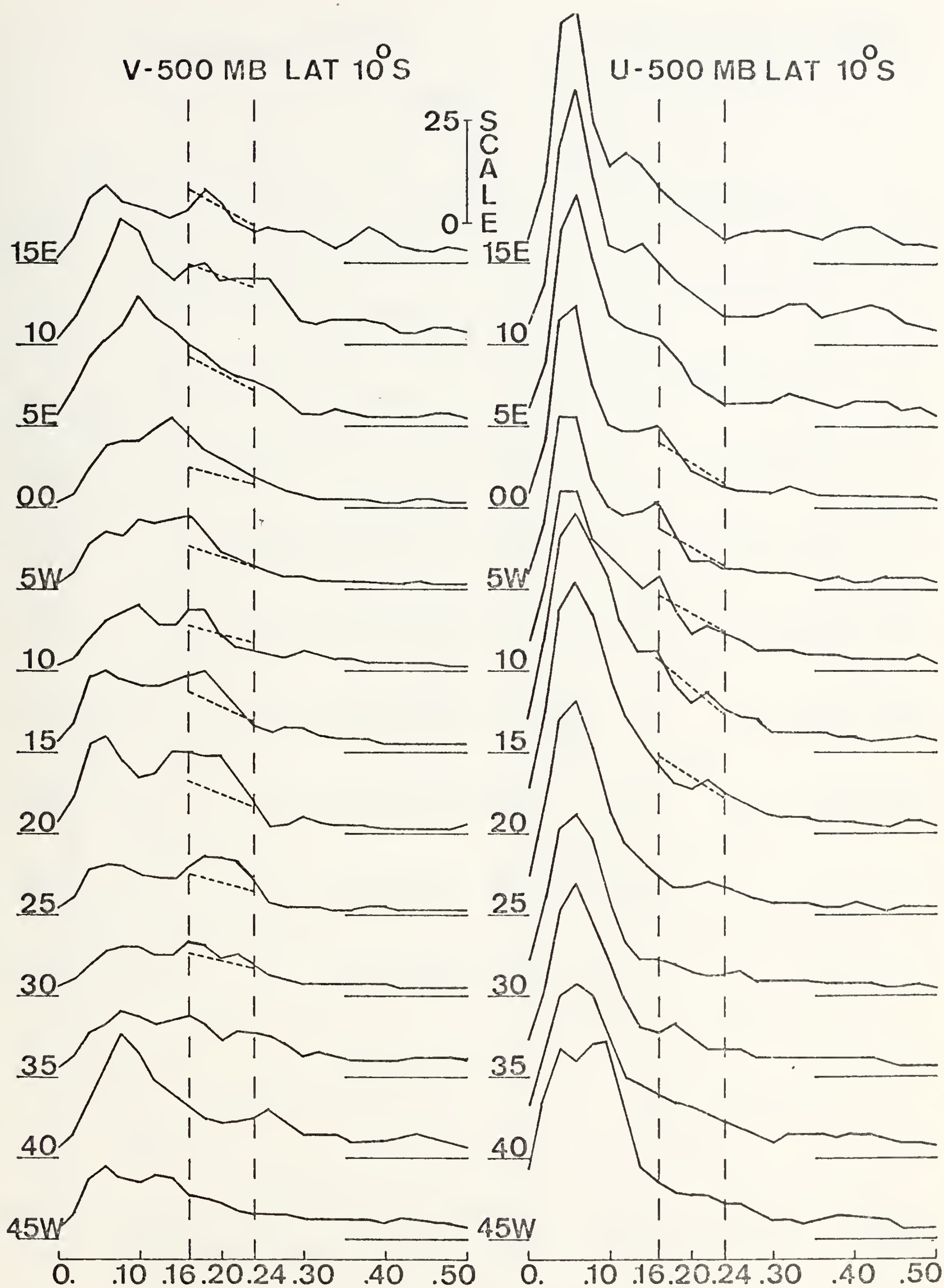

FIGURE 5(c) - Same as FIGURE 4(a), except for 500 mb and 10°S.

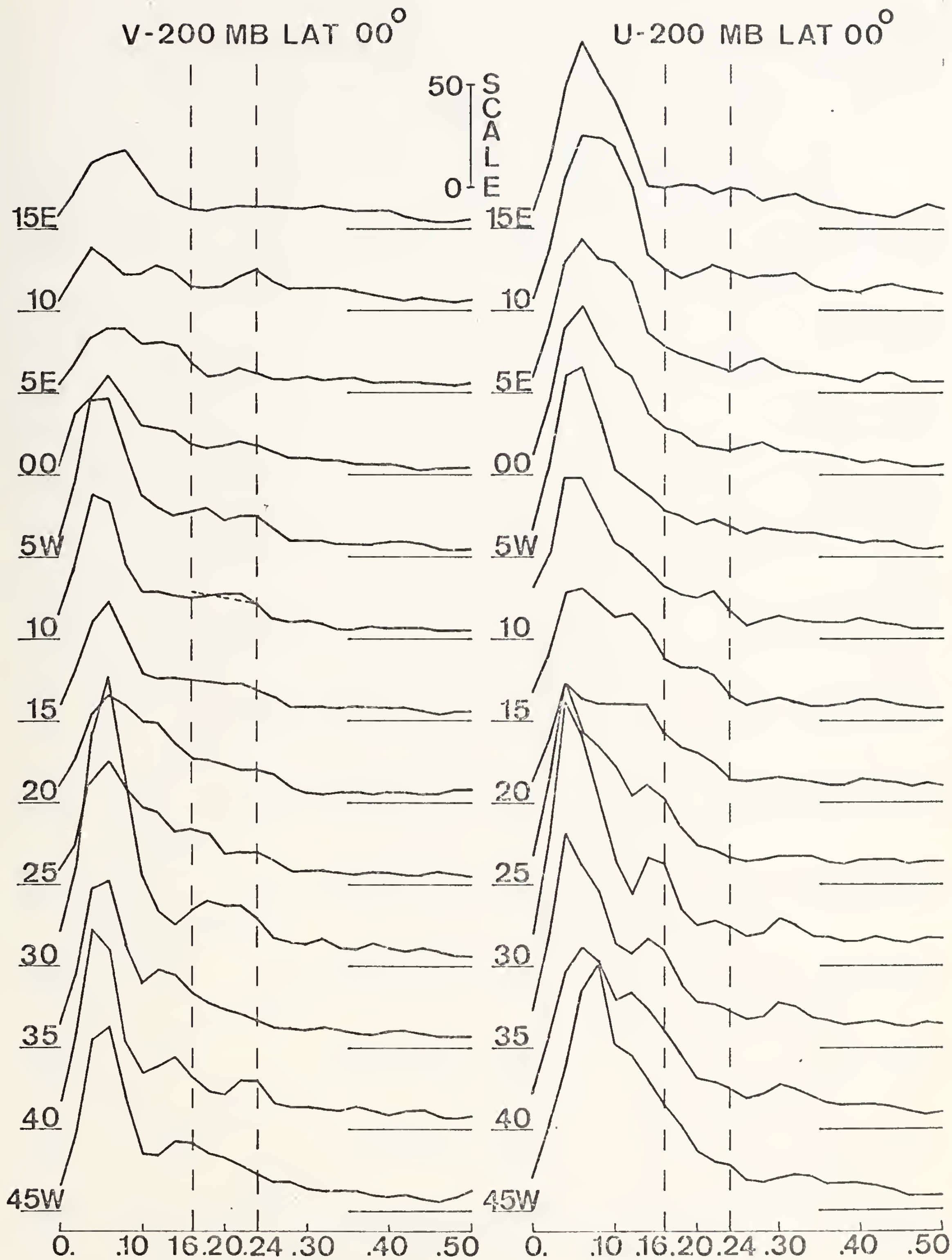

FIGURE 6(a) - Same as FIGURE 4(a), except for 200 mb and the equator.

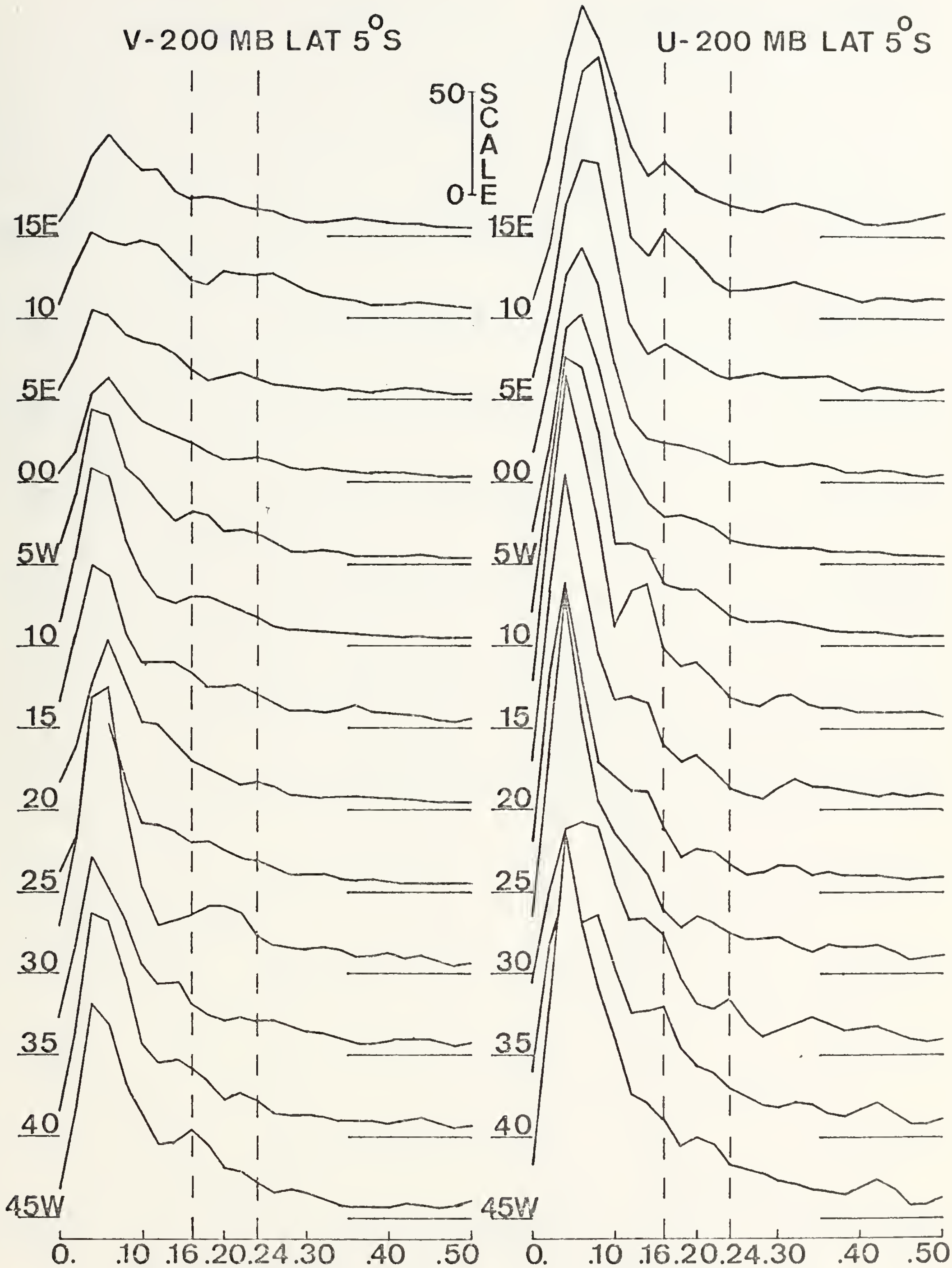

FIGURE 6(b) - Same as FIGURE 4(a), except for 200 mb and 5°S.

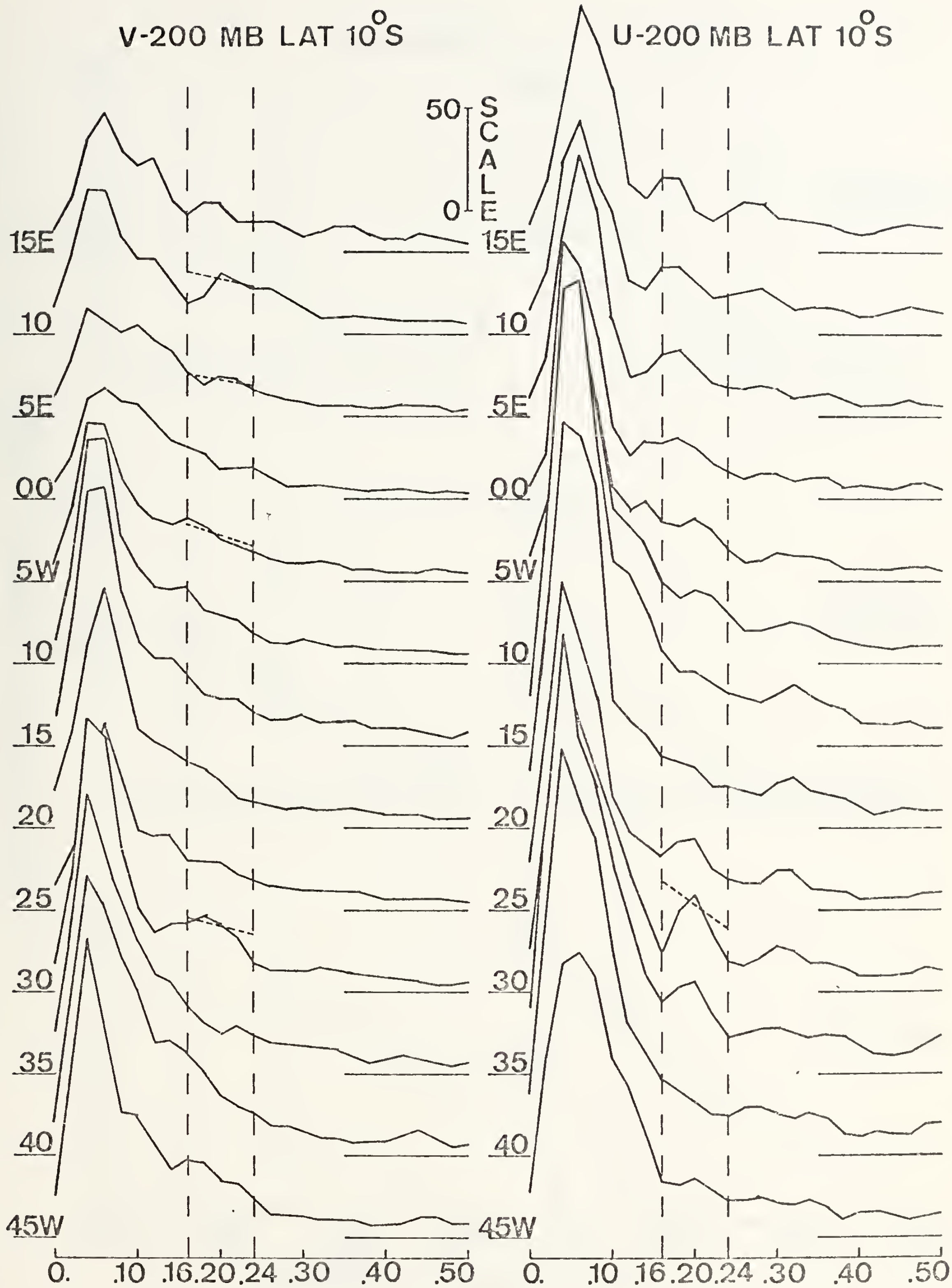

FIGURE 6(c) - Same as FIGURE 4(a), except for 200 mb and 10°S.

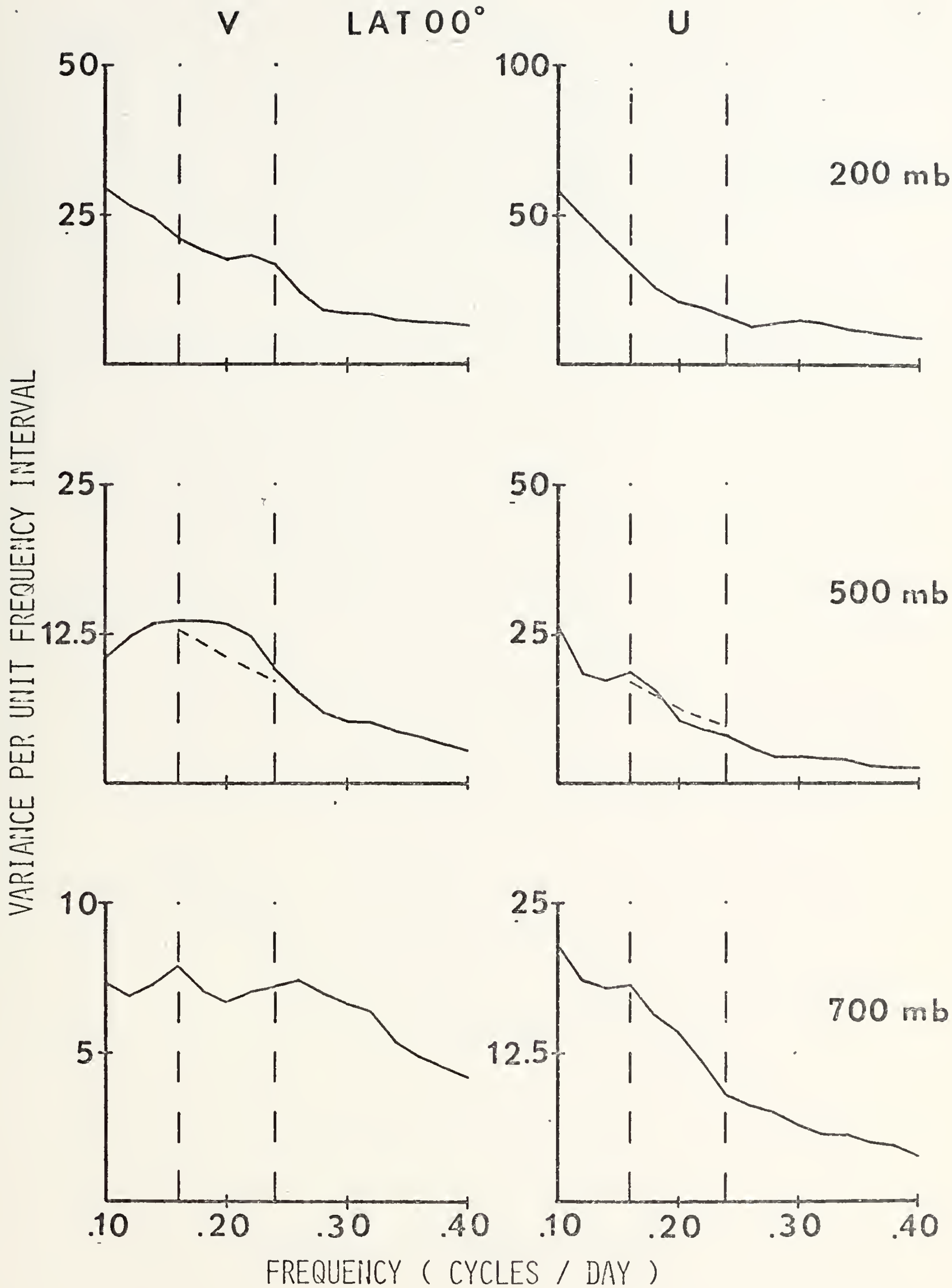

FIGURE 7(a) - Composite spectra (knot^2 per 2 π /50 day^{-1}) for the equator. The 95% confidence limit in the band 0.16-0.24 cpd is drawn whenever the variance in the band exceeds the limit.

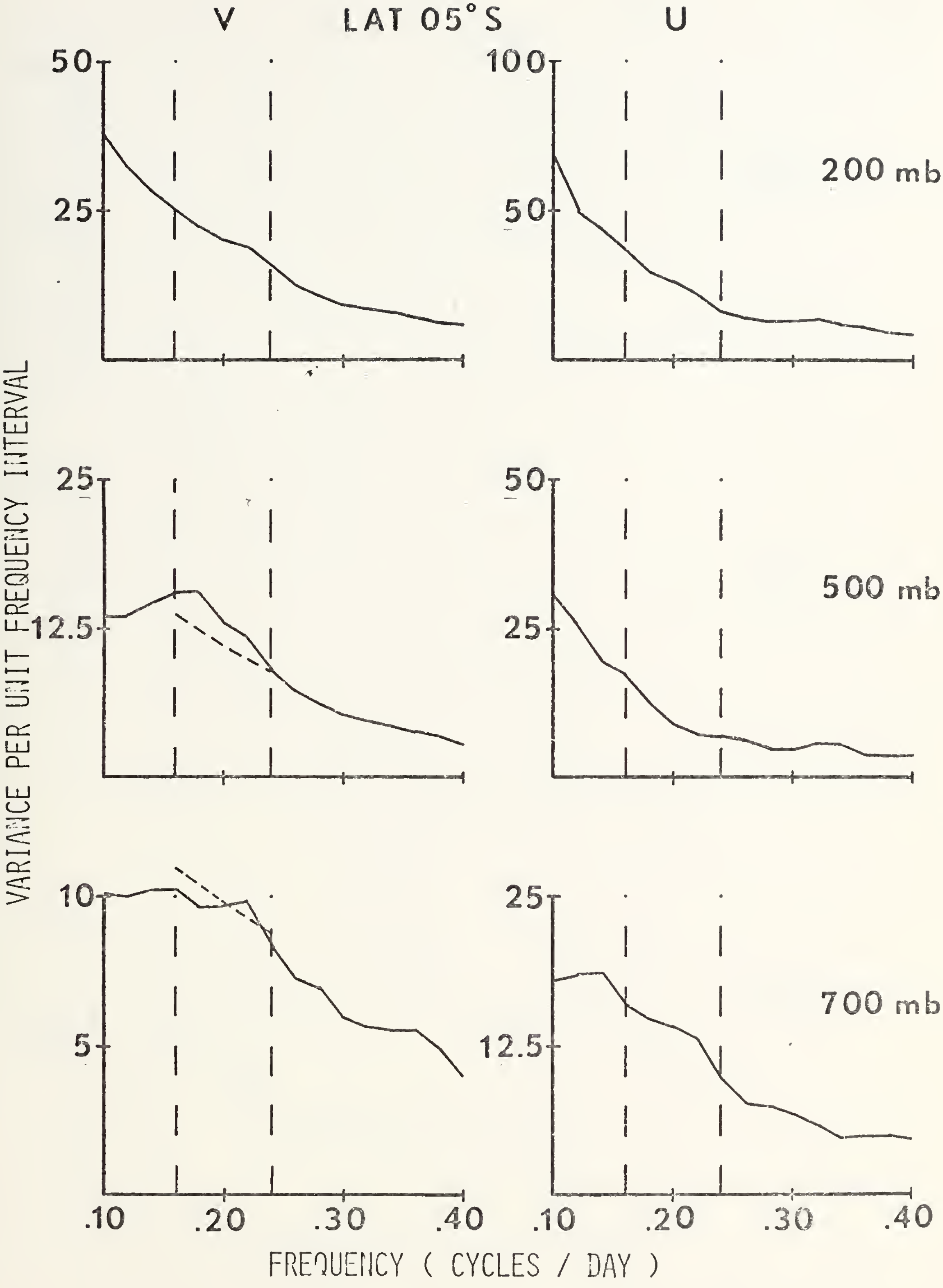

FIGURE 7(b) - Same as FIGURE 7(a), except for $5^{\circ}S$.

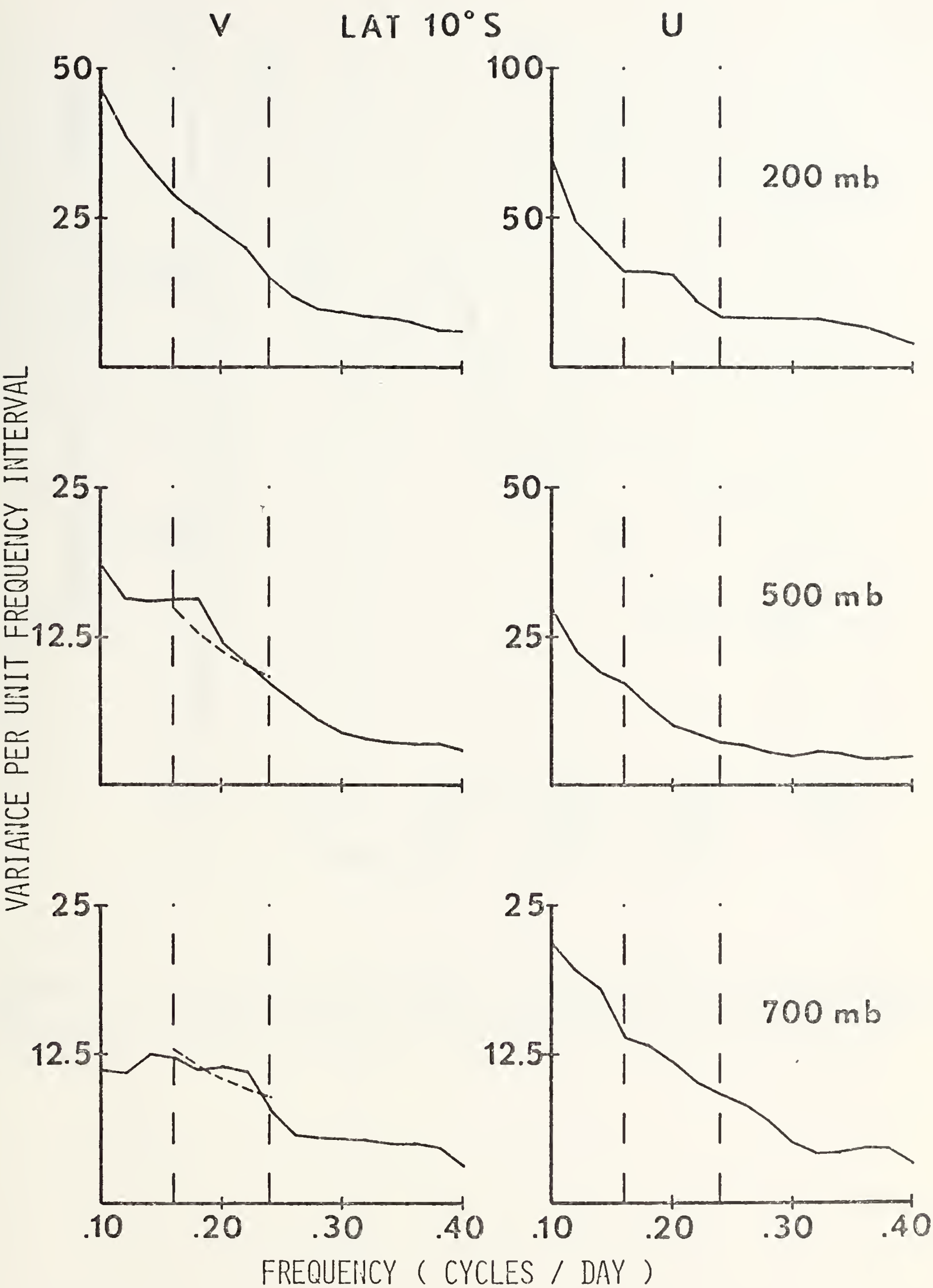

FIGURE 7(c) - Same as FIGURE 7(a), except for 10°S.

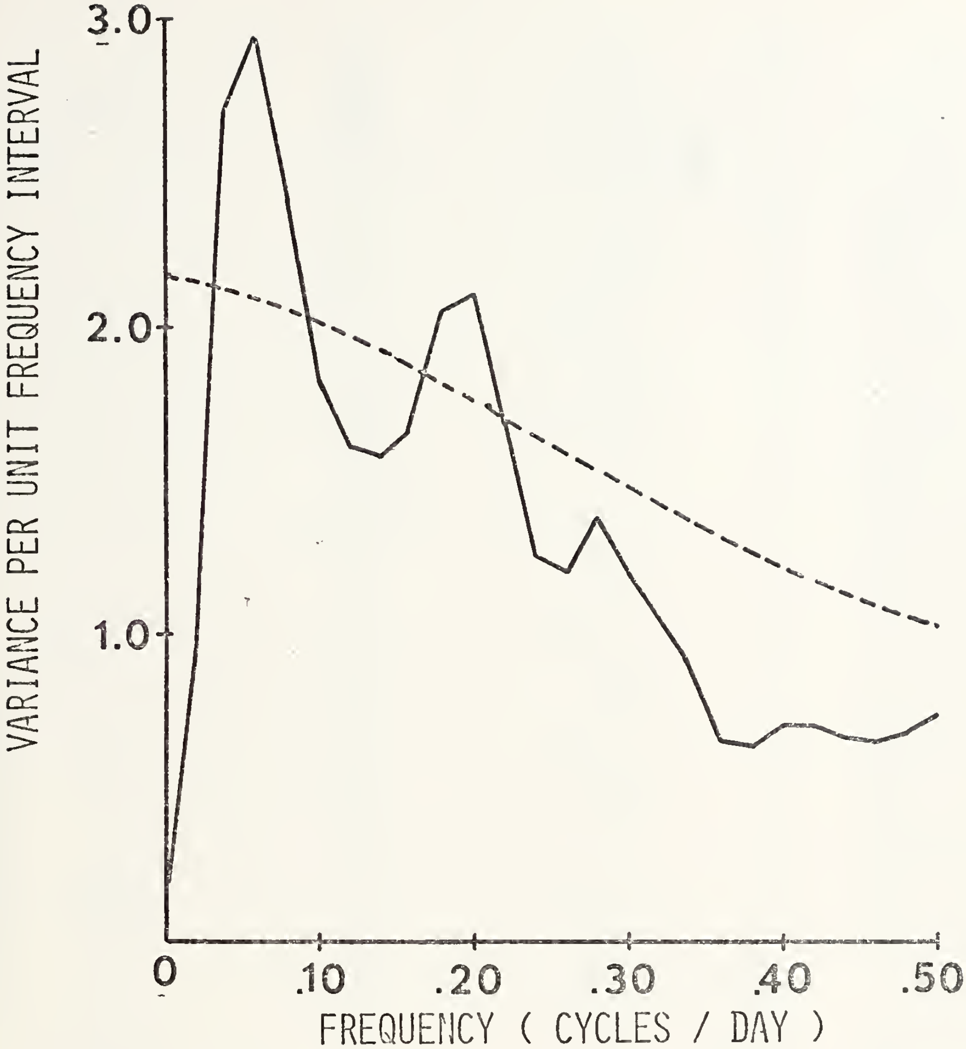

FIGURE 8 - Vertically averaged spectrum (m^2 sec^{-2} per 2/50 day^{-1}) for the 12 lowest levels of the v series at Parnaiba Airport. The 95% confidence limit is depicted by the dashed line.

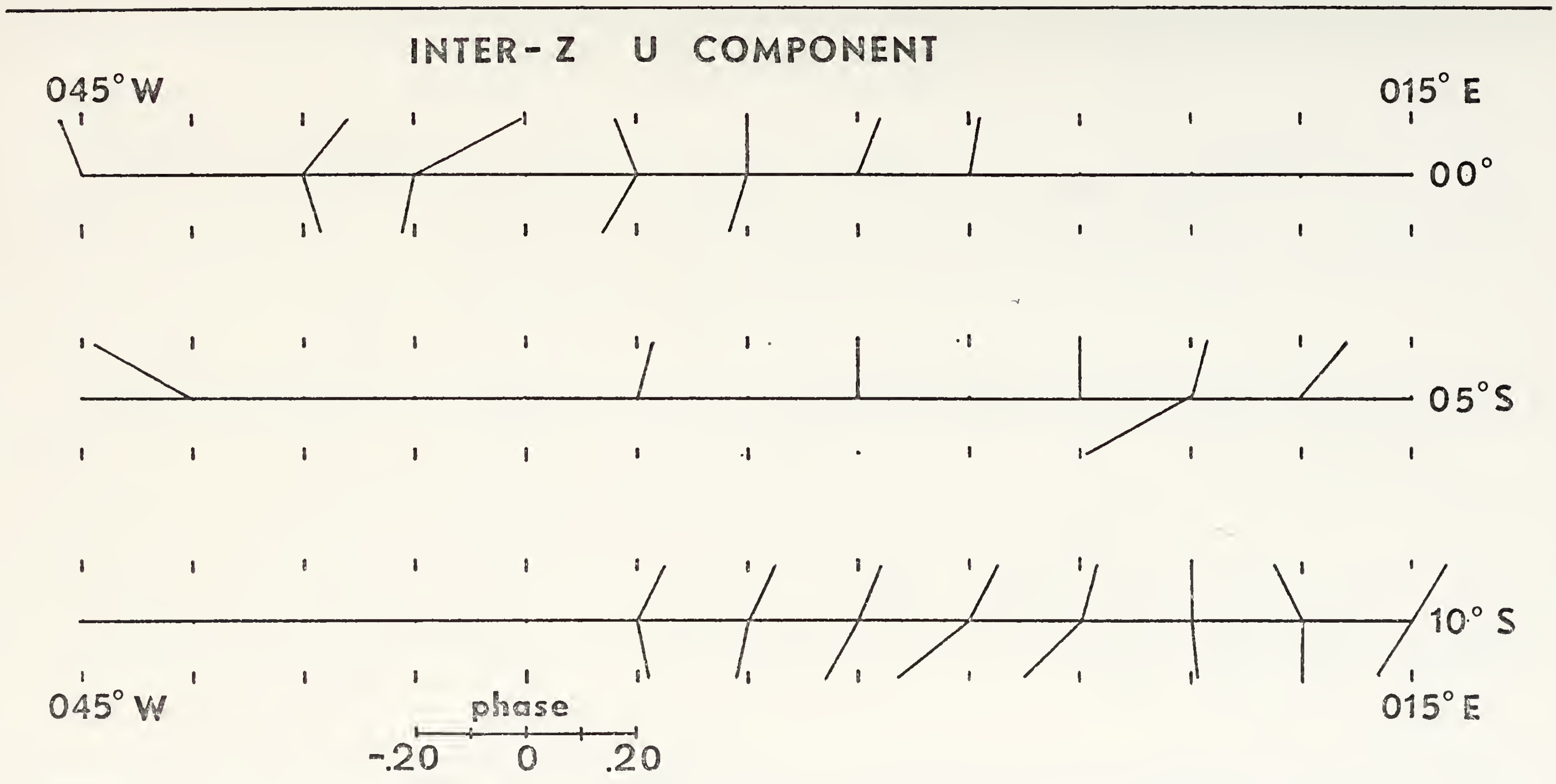

FIGURE 9(a) - Inter-level phase relationships for the grid-point u series. At each grid point a line is drawn to indicate the phase difference between the base series (500 mb) and the other series (200 mb for the upper mark, 700 mb for the lower mark) whenever the corresponding coherence-square meets the 95% confidence requirement.

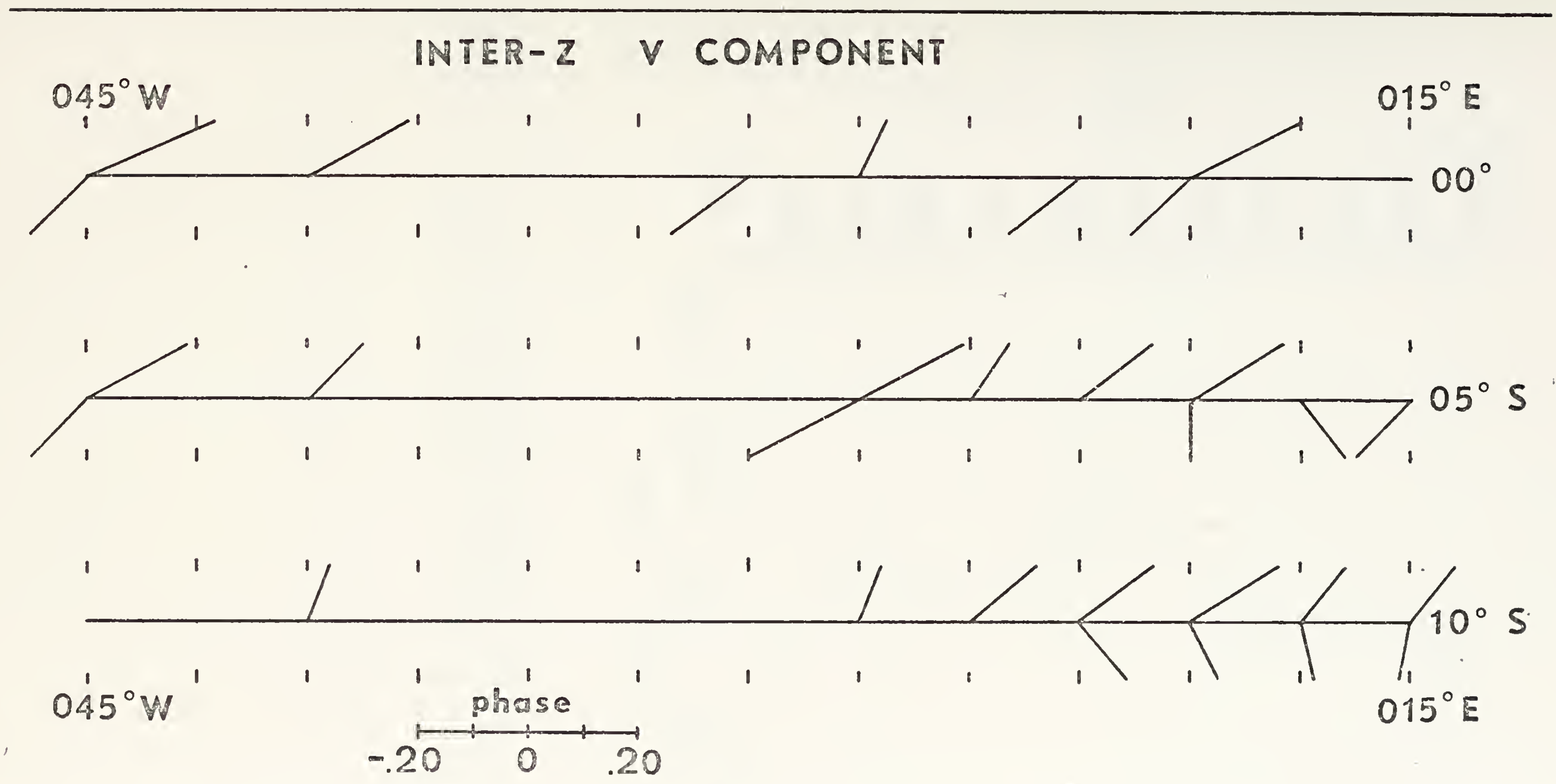

FIGURE 9(b) - Same as FIGURE 9(a), except for the v series.

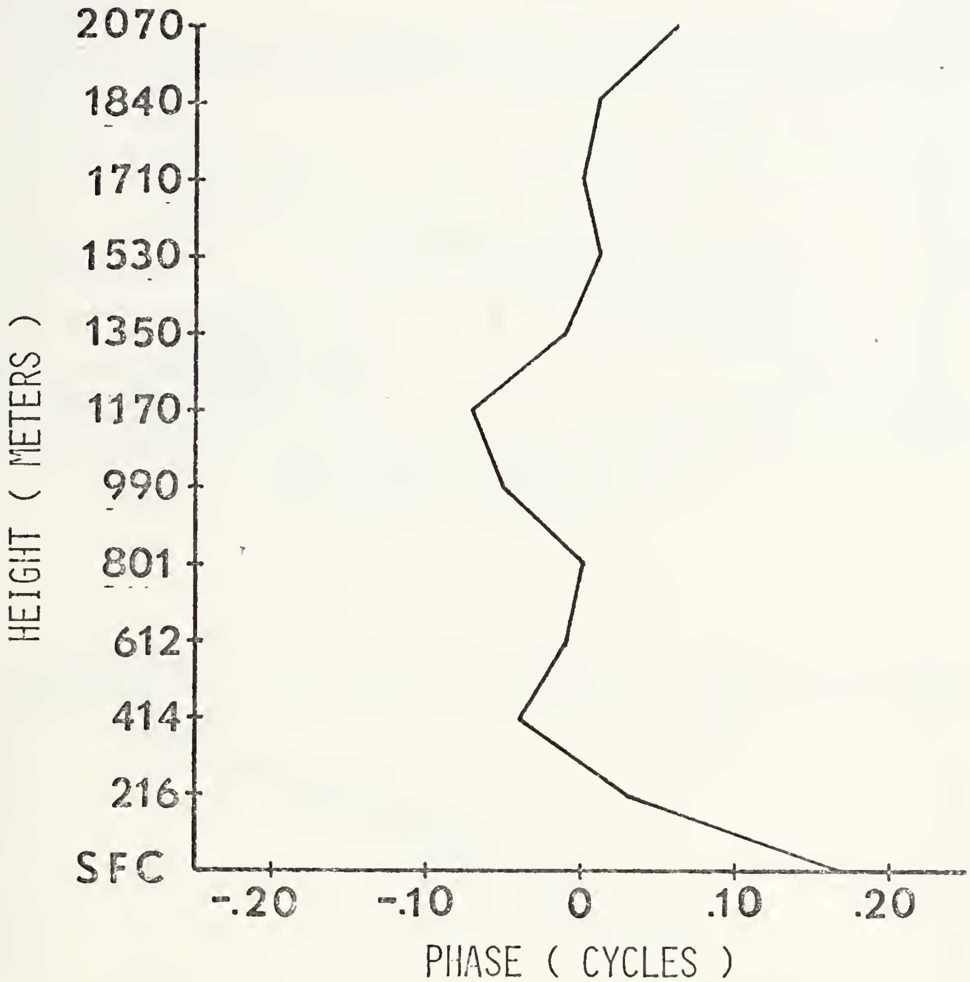

FIGURE 10 - Inter-level phase relationship at Parnaiba Airport. The base series is 801 m. All the corresponding coherence square values meet the 95% confidence requirement.

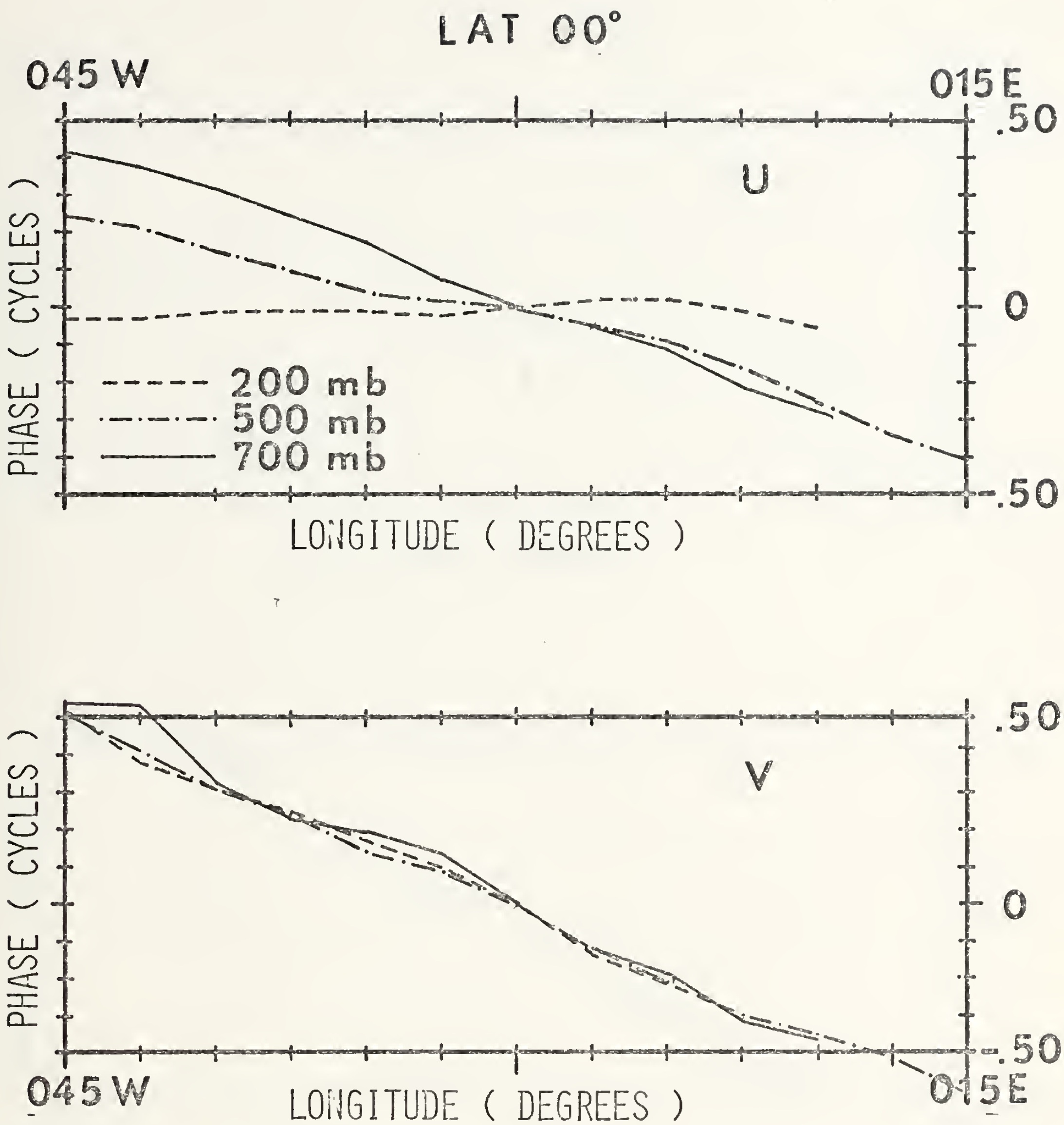

FIGURE 11(a) - Inter-longitude phase relationships at the equator. The base series is 15°W. Positive phase differences indicate that the base series leads the others. Only values with corresponding coherence square exceeding the 95% confidence limit are plotted.

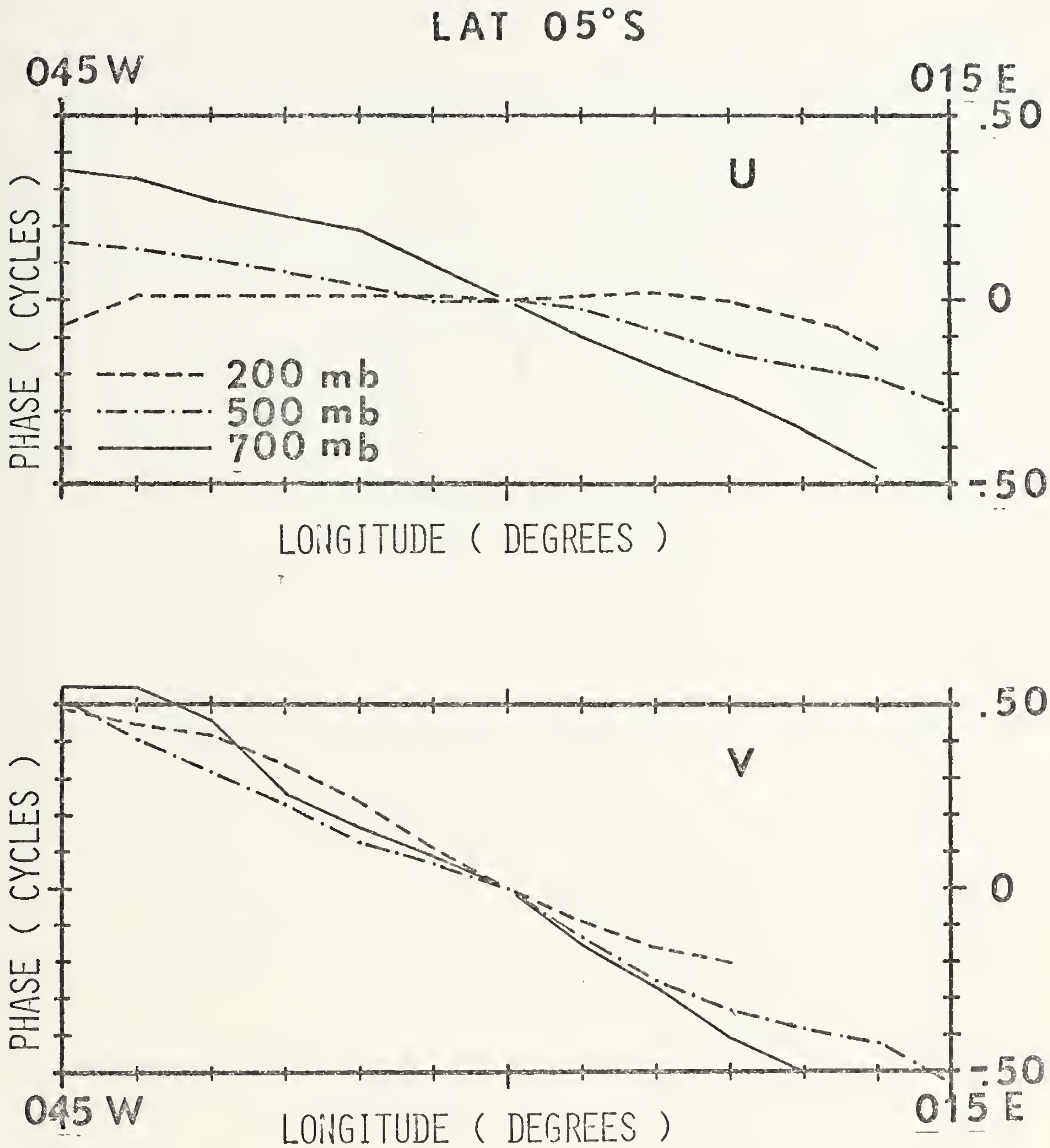

FIGURE 11(b) - Same as FIGURE 11(a), except for 5^{o}S.

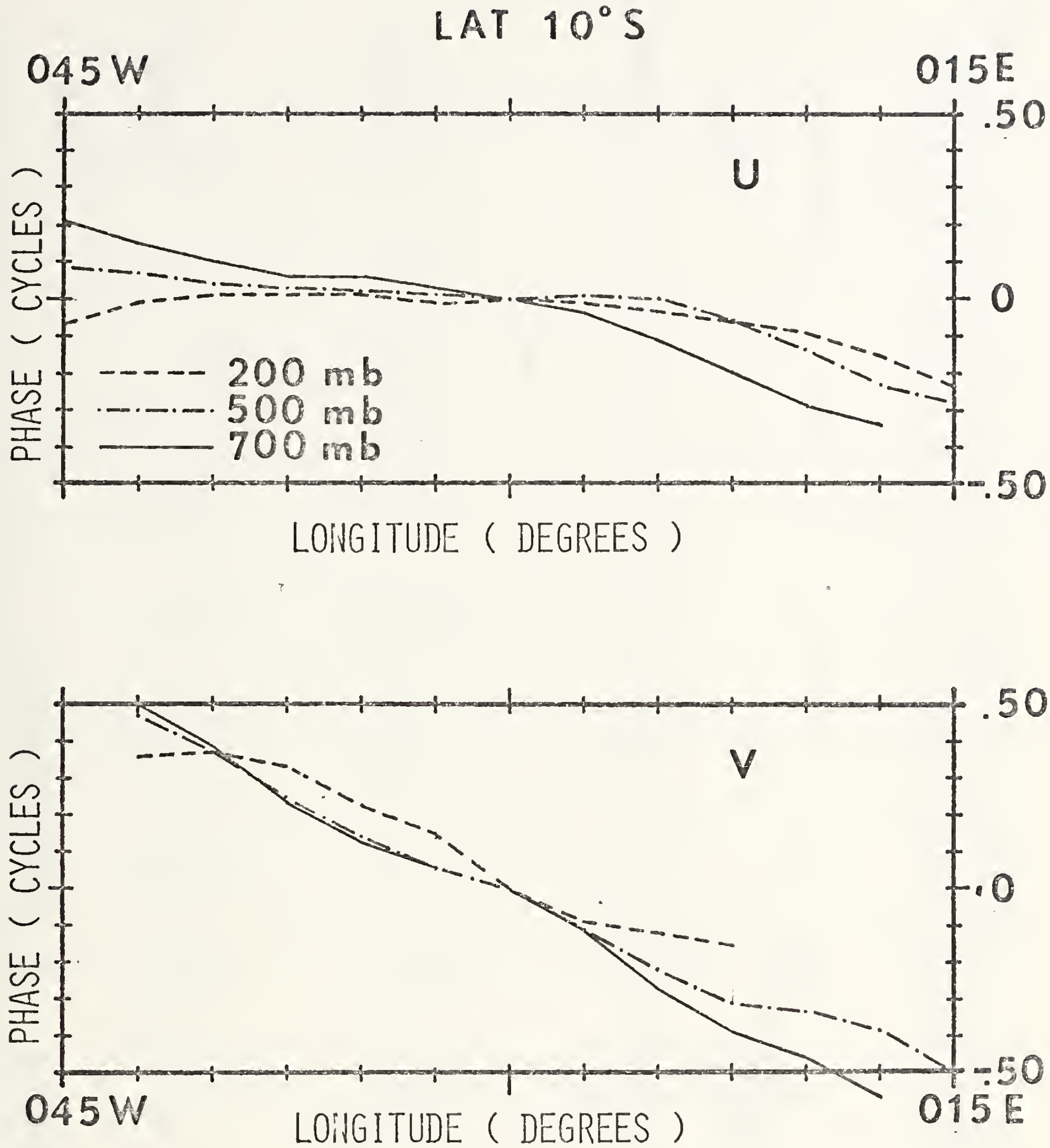

FIGURE 11(c) - Same as FIGURE 11(a), except for 10°S.

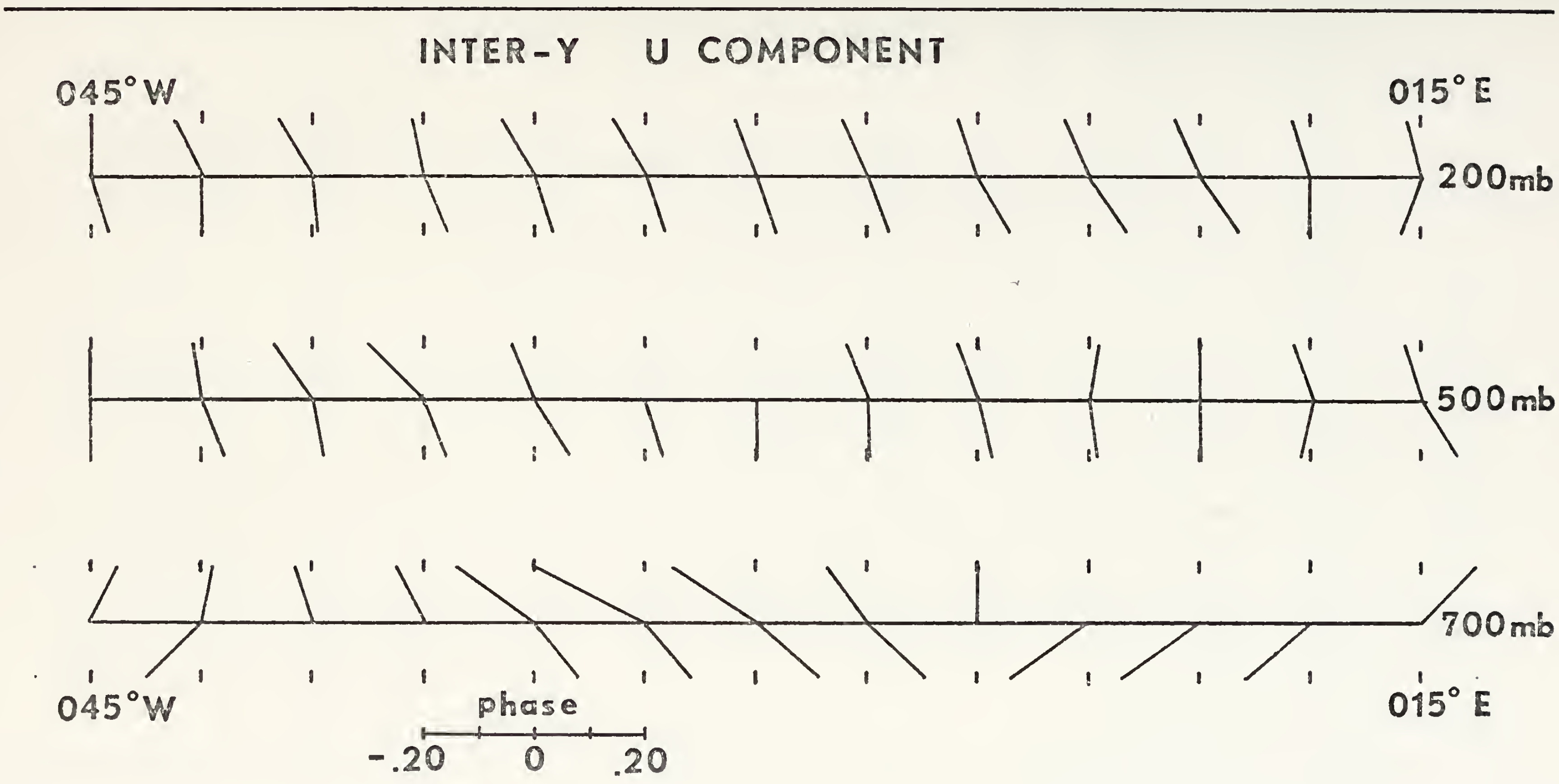

FIGURE 12(a) - Inter-latitude phase relationship for the grid point u series at each level. At each grid point a line is drawn to indicate the phase differences between the base series (5°S) and the other (equator for the upper mark, 10°S for the lower mark) whenever the corresponding coherence-square meets the 95% confidence requirement.

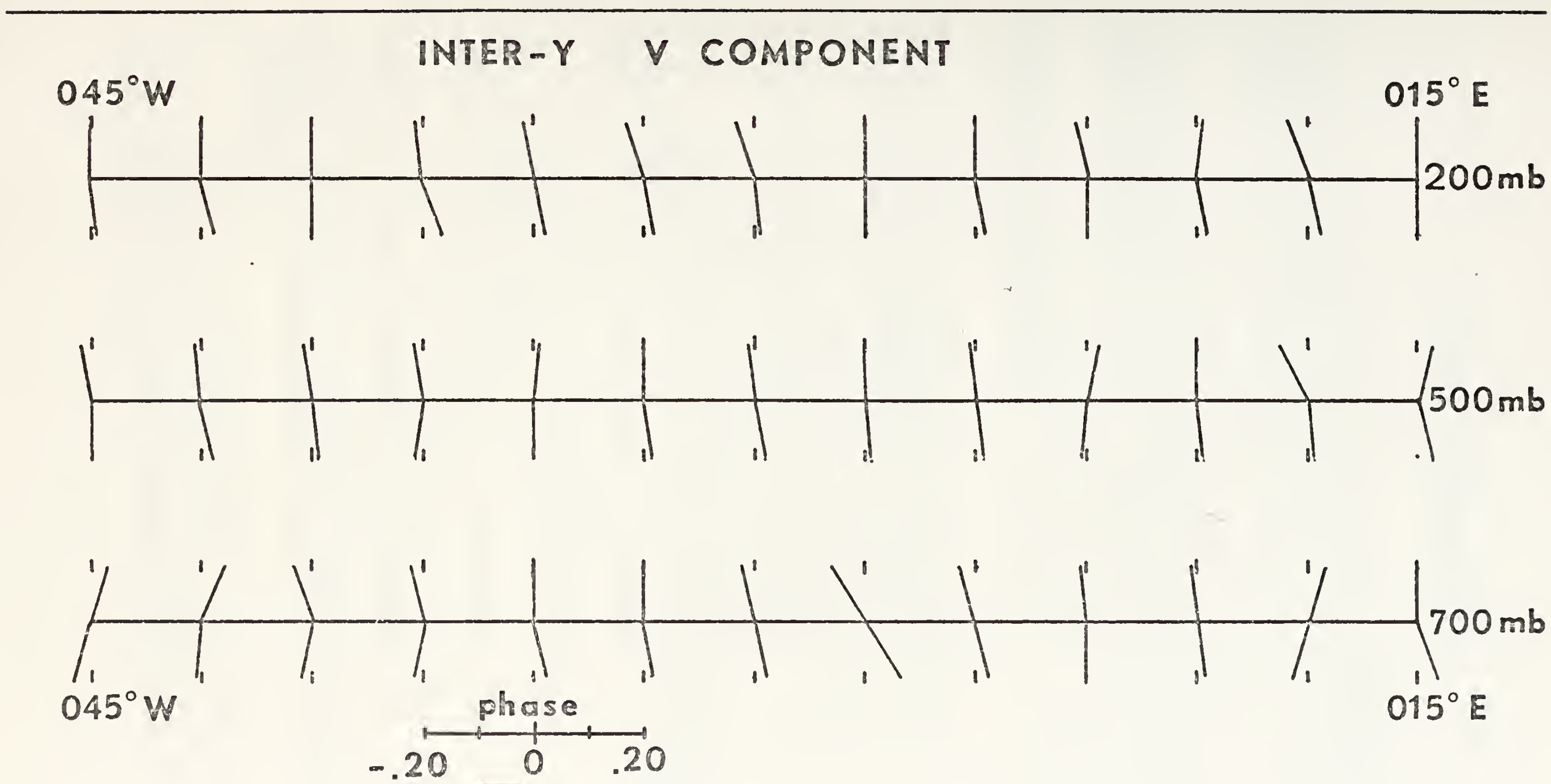

FIGURE 12(b) - Same as FIGURE 12(a), except for the v series.

LIST OF REFERENCES

Amos, D. E., and Koopmans, L. H., 1963: Tables of the distribution of the coefficient for coherence for stationary bivariate Gaussian processes. Scandia Corp., Albuquerque, N. M., Mono. SCR-483.

Bedient, H. A. and Irwin, J. R., 1970: National Meteorological Center's operational tropical analysis procedures. Proceedings of the Symposium on tropical Meteorology, June 2-11 1970, pp G-I. American Meteorological Society.

Brooks, C. E. P. and Carruthers, N., 1953: Handbook of statistics applied to Meteorology. His Majesty's Stationary Office, London, 412 pp.

Burpee, R. W., 1972: The origin and structure of easterly waves in the lower troposphere of North Africa. Journal of the Atmospheric Sciences, 29, 77-90.

Burpee, R. W., 1974: Characteristics of North African easterly waves during the summers of 1968 and 1969. Journal of the Atmospheric Sciences, 31, 1556-1570.

Chang, C. -P., 1970a: Westward propagating cloud patterns in the tropical Pacific as seen from time-composite satellite photographs. Journal of the Atmospheric sciences, 27, 133-138.

Chang, C. -P., Morris, V. F. and Wallace, J. M., 1970b: A statistical study of easterly waves in the Western Pacific: July-December 1964. Journal of the Atmospheric Sciences, 27, 195-201.

Gruber, A., 1974: On streamline patterns and momentum transports. Journal of the Atmospheric Sciences, 31, 1161-1163.

Mbele-Mbong, J., 1974: Rainfall in West Central Africa. Atmospheric Science Paper No. 222, Colorado State University, 126 pp.

Mitchell, J. M., Jr., Dzerdzeevskii, B., Flohn, H., Hofmeyer, W. L., Lamb, H. H., Rao, K. N., Wallen, C. C., 1966: Climatic Change. WMO Technical Note No. 79, WMO, Geneva, Switzerland, 79 pp.

Nitta, T., 1970: Statistical study of tropospheric wave disturbances in the tropical Pacific region. Journal of the Meteorological Society of Japan, XXXXVIII, 47-60.

Ramos, R. P. L., 1974: Precipitation characteristics in the Northeastern Brazil dry region. Atmospheric Science Paper No. 224, Colorado State University, 56 pp.

Reed, R. J. and Recker, E. E., 1971: Structure and properties of synoptic-scale wave disturbances in the equatorial Western Pacific. Journal of the Atmospheric Sciences, 28, 1117-1133.

Wallace, J. M. and Chang, C. -P., 1969: Spectrum analysis of large-scale wave disturbances in the tropical lower atmosphere. Journal of the Atmospheric Sciences, 26, 1010-1025.

Wallace, J. M., 1971: Spectral studies of tropospheric wave disturbances in the tropical Western Pacific. Reviews of Geophysics and Space Physics, 9, 557-611.

Yanai, M., Maruyama, R., Nitta, R. and Hayashi, Y., 1968: Power spectra of large-scale disturbances over the tropical Pacific. Journal of the Meteorological Society of Japan, XXXXVI, 308-323.

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